A CAPACITATED LOT SIZING AND SCHEDULING MODEL WITH SEQUENCE-DEPENDENT SETUP COSTS AND SETUP TIMES TO IMPROVE THE TACTICAL PRODUCTION PLANNING OF FRIESLANDCAMPINA.

A master thesis which analyzes the tactical production planning of a FrieslandCampina plant and proposes a model to determine optimal cycle stock levels and drumbeat patterns.

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PREFACE

In front of you lies a report that is the result of my graduation project to acquire my master's degree in Industrial Engineering and Management, with the specialization in Production and Logistics Management.

Major thanks to Matthieu van der Heijden, for his guidance throughout the whole project, and for always proving extensive feedback on my work, both on the structure and the contents. Thank you for all the quick responses and the time we spent together in online meetings. Your encouraging and positive attitude means a lot to me. In addition, thanks to my second supervisor, Leo van der Wegen, for his in-debt knowledge and support that sharpened my view.

Furthermore, I would like to thank Patrick Veeloo who gave me the opportunity to do my graduation project at FrieslandCampina. Despite the work-from-home situation, you made me feel like I was a part of the team, which allowed me to work on my graduation project with great enthusiasm. In addition, you have made me think about my future and we discussed together which direction I want to go. I am grateful to you for all the time you have invested in me to learn and grow as a person. Thanks also to all my colleagues and a special thanks to Lianne Takken for all the virtual coffee dates.

Finally, I would like to thank my family and friends for their love, support and advice. A special thanks to my boyfriend for always listening to me and making me feel more optimistic and encouraged.

I hope you will enjoy reading this master thesis!

Liza Snellen

Utrecht, June 2021

MANAGEMENT SUMMARY

This thesis is carried out together with the Supply Planning Department of FrieslandCampina. FrieslandCampina is one of the world's largest dairy companies with a cooperative tradition going back almost 150 years. In this research, the focus is on the plant in Aalter (Belgium), which is one of the four Royal FrieslandCampina (RFC) Plants. The plant produces around 440 million kilos of finished products each year on 17 packaging lines. This plant is responsible for around 70% of the total stock value of FrieslandCampina. One of the projects to reduce the stock value of Aalter is to optimize the drumbeat patterns and the cycle stocks of the plant in Aalter. In this research, we aim to find an answer to the following main research question: "*How can FrieslandCampina optimize costs between setup and inventory of the plant in Aalter by developing a tactical production planning tool using the optimal cycle stock levels and drumbeat patterns of all SKUs?".*

The plant in Aalter operates according to the make-to-stock method. The process of operational demand & production planning starts with creating a forecast for the upcoming 18 months. Next, the Advanced Planning & Optimization (APO) tool constructs a production planning for the next 13 weeks. The supply network planners check this planning because APO plans according to an unrestricted method. To obtain an accurate planning, FrieslandCampina designed drumbeat patterns for each SKU. The drumbeat patterns represent four weeks and are made of 4 digits consisting of a combination of ones and zeros; one represents production and zero represents no production. The drumbeat patterns are key for the plant and control almost all KPIs. After several projects, they have not yet found a good method to calculate the optimal drumbeat patterns.

Based on our literature review, we find that determining lot sizes including sequence-dependent setup costs and setup times is challenging and requires difficult mathematical models. These models aim to find an optimal trade-off between setups in production and keeping inventory. In this research, we face a problem which is a multi-item problem with dynamic demand. Several capacity constraints must be included in the model and there are multiple items produced during one time period, which indicates a large-bucket situation. Therefore, our problem is mostly related to the capacitated lot sizing problem, which is a mixed integer linear programming (MILP) model. To incorporate the sequence-dependent setups, we introduce product families. The MILP model considers these setups between product families but also at the recipe level, and when a format changeover is required. The model includes the minimum and maximum production quantities at the recipe level as well. The objective function of the model minimizes the setup costs at the product family level, setup costs at the recipe level, setup costs for changing a format on a packaging line, holding costs and capital costs. We first do a pilot with packaging line 'U' of which the results look promising. Therefore, we decide to continue with our model in Microsoft Excel and to extend this pilot to all packaging lines.

In the MILP model, we consider multiple decision and auxiliary variables, resulting in a large decision space with a very long running time. To overcome this problem and to make the model usable for FrieslandCampina we can reduce the number of variables by excluding packaging lines of the main model. To do this analysis we introduce three different scenarios to which we adjust the model:

- All packaging lines included in one model.
- Divide the packaging lines into groups and solve the model for the groups separately.
- Design a model for all packaging lines separately.

In the first option, we do not find a solution within twelve hours because of the enormous decision space. In the second option, we only find a feasible solution for group two and group three within 12 hours. A good analysis of this option is therefore not possible. In the third option, we only not find a solution within twelve hours for packaging line '*R*'. For all the other packaging lines we find an (optimal) solution within four hours. The total savings on all these packaging lines can be 10% of the total costs. The total capacity utilization of all packaging lines can be reduced by 7%.

To enlarge the possibility of obtaining a feasible solution in a reasonable time for the three groups, we simplify the models in different ways. First, we reduce the number of drumbeat pattern options and second, we remove the integer constraints of the production quantities. Removing the integer constraint has a huge impact on the running time of the models and only minimal impact on the solution. We find the best solution when we combine both options for the three groups.

Due to these promising results, we again run the model with all packaging lines together but without the integer constraint of the production quantities. Moreover, based on the column generation algorithm, we only include the most likely drumbeat patterns per product family. With these improvements, we find a solution for the model with all packaging lines in four hours. The results show that a saving of 7% on setup costs and 4% on inventory costs can be achieved. The total costs can be reduced by 9%. If we analyze this solution, we see that the average capacity utilization over all packaging line can be reduced by 5%. The bottleneck in the production process of the plant is the preparation of the recipes, which is bounded by minimum and maximum production quantities. The distribution of cream production over the weeks is most challenging. In the solution of the model with all packaging lines included, the average production of cream is 99%, which means that almost in each week the maximum production quantity is made.

The sensitivity analysis shows that our model is robust. The deviations of the total costs are between 0 and 8%, while we changed the input parameters by 5% and 10%. By changing the ratio between setup and inventory costs or the forecast, the number of productions remains almost the same, but the drumbeat patterns differ in order. We can conclude that the optimization is mainly driven by cleverly combining products and merging them into a product family to reduce the number of setups.

To conclude the findings of this research, we recommend waiting and analyzing the results of the pilot with packaging line *'U'*. If all results are positive and the results are as expected, the drumbeat patterns of the other packaging lines can be validated and implemented. Based on the process of determining the cost drivers, we advise FrieslandCampina to collect the input data to increase the accuracy of the decisions made by the model. Collecting this data would not only lead to cost savings by implementing the results of the model but also helps with monitoring possible outliers.

We recommend FrieslandCampina to convert the model into another format, such as CPLEX or AIMMS or to use heuristics to generate a (near) optimal solution. Column generation could be used, by changing the likely drumbeat pattern options per product family. On the other hand, simulated annealing could be useful to obtain a solution in less computation time. In addition, we advise FrieslandCampina to save the planning generated by APO, to make it possible to analyze the behavior of the drumbeat patterns. Furthermore, extensive research can be done on the impact of the created product families. Due to the complexity, the model proposed should not be expected to completely substitute a human expert in the production planning process. Rather, it can be viewed as a tool that can generate an initial solution and provide valuable guidance to the managers of FrieslandCampina.

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GLOSSARY

APO	Advanced Planning & Optimization (tool integrated in SAP)
CD	Consumer Dairy
CIP	Cleaning-in-place
CLSP	Capacitated Lot Sizing Problem
CSC NL	Customer Supply Chain Nederland
DIO	Days Inventory Outstanding (overreaching project)
EBQ	Economic Batch Quantity
EOQ	Economic Order Quantity
ERP	Enterprise Resource Planning
MILP	Mixed Integer Linear Programming
MRP	Material Requirement Planning
MVA	Milk Valorisation & Allocation
NS	Neighbourhood Solution
O&D	Ontvangst & Dispatch
OEE	Overall Equipment Effectiveness
OP&PP	Operational Demand & Production Planning
RFC	Royal FrieslandCampina
SA	Simulated Annealing
SAP	German Company Name: Systeme, Anwendungen und Produkte in der Datenverarbeitung
SCV	Squared Coefficient of Variation
SKU	Stock Keeping Unit: a unique finished product
SNP	Supply Network Planners
VMI	Vendor Managed Inventory
WACC	Weighted Average Cost of Capital

1. INTRODUCTION

In the context of completing the Master Industrial Engineering and Management, we conduct this research at FrieslandCampina. In this chapter, we introduce FrieslandCampina and the department on behalf of which this research is conducted in Section 1.1. In Section 1.2, we explain the motivation of this research and the corresponding problem statement in Section 1.3. Next, we formulate the goal of this research in Section 1.4, as well as the research questions that must be answered to reach this goal in Section 1.5. We also provide an overview of the structure of the report in Section 1.6. Finally, Section 1.7 covers the scope and deliverables of the research.

1.1 COMPANY DESCRIPTION

Today, FrieslandCampina is one of the world's largest dairy companies with a cooperative tradition going back almost 150 years. Every day, they provide millions of consumers all over the world with valuable nutrition from milk. Besides milk and dairy products, they focus on specialized nutrition for specific groups of consumers with specific requirements. In 2019, 11,476 dairy farm members in the Netherlands, Germany, and Belgium supplied approximately a total of ten billion kilos of milk. FrieslandCampina has branch offices in 36 countries and their products find their way to more than 100 countries. At the end of 2019, FrieslandCampina employed 23,816 workers (FrieslandCampina, 2020). In the figure below the organogram of a part of the company is shown. The department of which I am part of during this research is indicated blue.

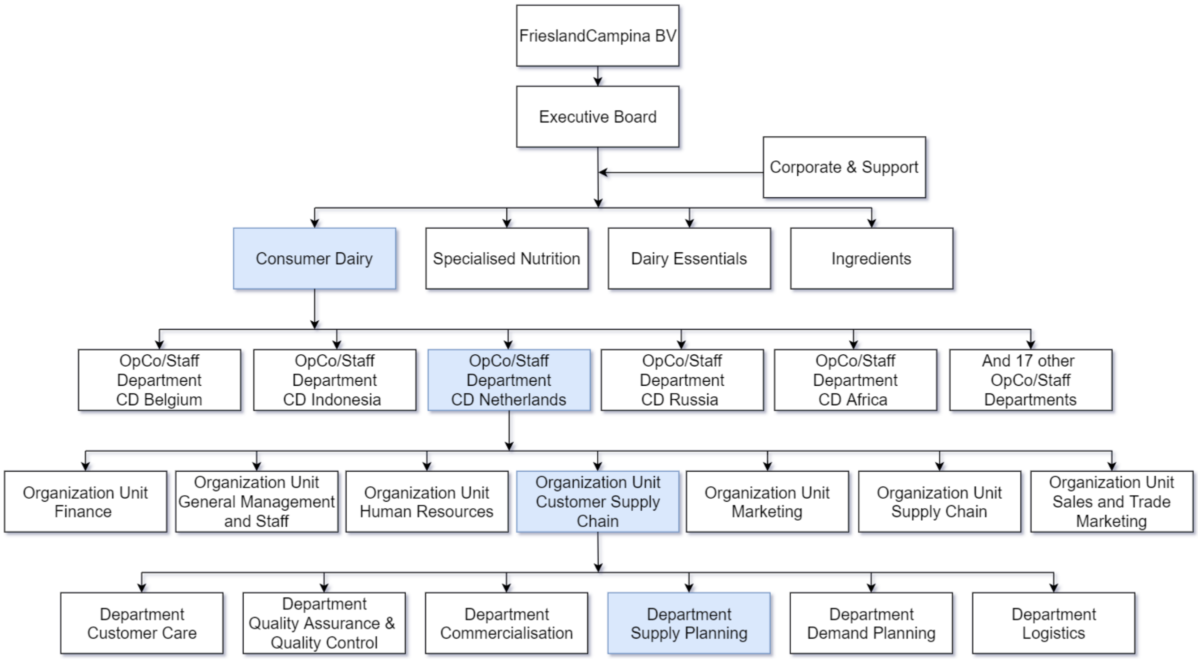

Figure 1: Organogram of FrieslandCampina

As you can see, the activities of FrieslandCampina are divided into four business groups: Consumer Dairy, Specialised Nutrition, Dairy Essentials, and Ingredients. Each of the business groups ensures the development, production, and sales of dairy products in a number of markets. My research will focus on the products from the business group Consumer Dairy, which is consumer driven. It has a strong dairy portfolio of regionally relevant branded products, such as condensed milk, yoghurt, quark, dairy-based beverages, and cheese (FrieslandCampina, 2020). I will be part of the Supply Planning Department, which is an element of the Organization Unit Customer Supply Chain Nederland (CSC NL).

The goal of the Supply Planning Department is to deliver a realistic supply plan including raw and auxiliary materials needed with the desired service level and optimal costs as its focus. The Consumer Dairy Department of Belgium does not have its own Supply Planning Department and therefore these activities are under the responsibility of the team in the Netherlands. An overview of the characteristics of this team can be seen in Figure 2.

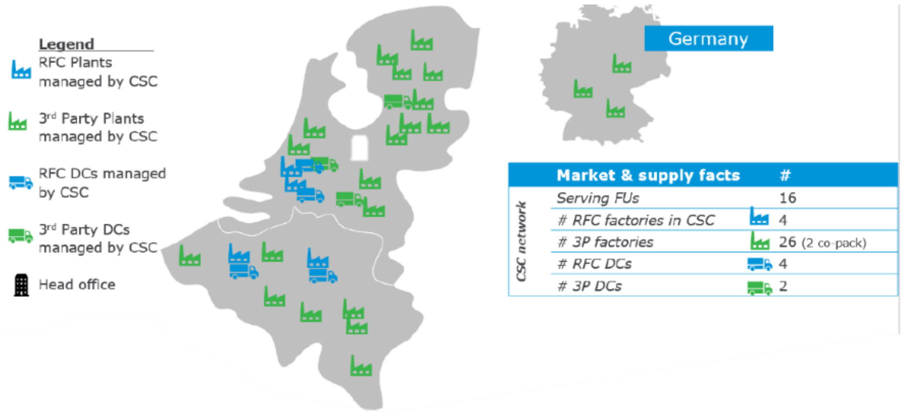

Figure 2: Portfolio of Customer Supply Chain Supply team NL

In this research, the focus is only on the plant in Aalter (Belgium), which is one of the four Royal FrieslandCampina (RFC) Plants managed by CSC NL (Supply Team CSC NL, 2019). This plant is fully focused on ambient product, such as coffee milk, flavoured drinks, milk, chocolate, yoghurt drinks, and whipped cream. The plant produces around 440 million kilos each year on 17 packaging lines, which produce all ambient products. The challenge of this plant is to supply 16 different Operating Companies, also called Fighting Units within FrieslandCampina, with a diversity of needs with a great variety of products. Moreover, the portfolio is constantly changing and action drives the volume. The products that are made in the plant in Aalter are stored in different warehouses in different countries with a stock value of around 20 million euros in December 2020 (Supply Team CSC NL, 2019).

1.2 Motivation research

At the end of 2019, FrieslandCampina saw the prognosis of a declining trend in the total sales towards the end of 2020 and took action to reduce the overall costs of the make. They came up with the project DIO, which stands for Days Inventory Outstanding, to reduce the overall stock value of FrieslandCampina. DIO is an efficiency metric used to measure the average number of days a company holds inventory before selling it and it is a good indicator of the health of FrieslandCampina's cash flow. The goal of this project was to save 3 million euros in 2020 through several smaller projects with a focus on reducing the stock value of FrieslandCampina. In December 2020, they reduced the stock levels by 5%, while increasing the service levels by 0.1% (Klinkenberg, 2020). Unfortunately, some quality stock projects are postponed to 2021, the main cause being the COVID Pandemic. One of the postponed projects is to optimize the drumbeat patterns and the cycle stocks of the plant in Aalter. Drumbeat patterns refer to the fixed production frequencies per SKU and the cycle stock is the amount of inventory that is planned to be used between the production cycles.

The plant in Aalter by itself is responsible for around 70% of the total stock value of FrieslandCampina. The main reason is the sole production of ambient products in Aalter, in comparison to the chilled products in the other RFC plants. Due to this high percentage, there is an urge to reduce the total stock value of the produced products in Aalter. In addition to this intern project, there is always the urge to reduce costs within the entire supply chain. Therefore, the focus of this research will be reducing the stock value of the plant in Aalter but other options for reducing costs will certainly also be examined.

1.3 PROBLEM STATEMENT

In this section, we provide a clear overview of the cause and consequence analysis to determine the core problem that we tackle in our research. The goal is to bring structure to the problem context and consequently identify the core problem that must be tackled. In Figure 3 this overview is given. The grey boxes show the action problems that the company faces. There are several causes for these problems, which are called the core problems. These core problems are indicated in blue.

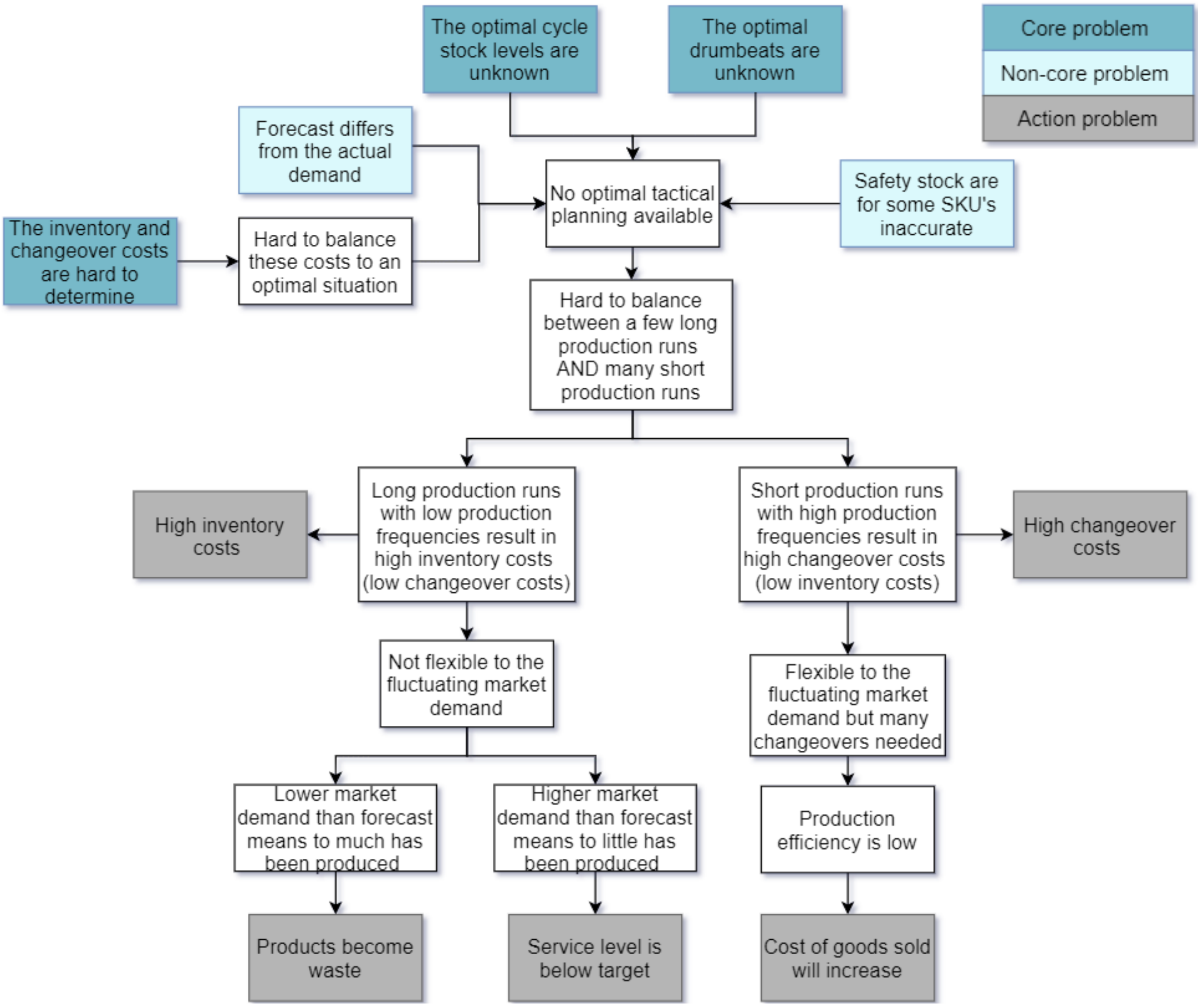

Figure 3: Cause and effect analysis

However, we do not tackle all the core problems in our research because some are out of scope or cannot be solved at all. This holds for the problem that the forecast differs from the actual demand. This would always be the case, or the demand must be known in advance, then no forecast is needed. The forecast accuracy is above target and therefore not an accurate problem to assess in this research. FrieslandCampina also faces the problem that the safety stocks are not accurate for all the SKUs. However, they are working on a promising tool and therefore it is not necessary to consider this problem for our research.

We described the causes that are out of scope, next, we identify the core problem. We find that the core problem is three-fold: the inventory and setup costs are hard to determine, the optimal cycle stock levels per SKU are unknown and the optimal drumbeat patterns per SKU are unknown. Right now, there is no fact-based method to make the trade-off between setup costs and inventory costs.

All these results are necessary to obtain a tactical planning for the plant. When all these optimal values are calculated they must be implemented before they show any results. Therefore, it is part of this research to obtain an optimal tactical planning for the plant, which can be implemented to reach optimal results. The problem identification results in the following problem statement:

> *"There is not enough insight in the inventory and setup costs and the optimal cycle stock levels and drumbeat patterns are unknown, causing a non-optimal tactical planning.*

This can result in high inventory costs with products that can become waste or a service level that can be below target. Or this results in high setup costs with an increase in the costs of goods sold.

1.4 Research Goal

The core problems as described in the previous section are likely to be part of the cause of the high costs. The goal of the plant in Aalter is to create a tool that they can use semi-yearly. This tool requires data that must be loaded every time you will use it, so it will do the calculations with the most accurate data. With all the data, the optimal drumbeat patterns for the coming half year will be calculated concerning the constraints and restrictions of the plant and each SKU. Think of including the capacity of the packaging lines as well as the best before date, such that the proposed drumbeat patterns are feasible. This tool will give the tactical planning an indication of which week each SKU must be produced for the coming six months. This can be different for some SKUs due to promotions or seasonality and it would be beneficial that these changes are highlighted. Based on this planning it will be possible to schedule the plant towards optimality, which will reduce the overall costs of the plant in Aalter. Therefore, the research goal is formulated as follows:

> *"Developing a tactical production planning tool including the optimal cycle stock levels and drumbeat patterns of all SKUs to find an optimal trade-off between the setup and inventory costs."*

It is important to include insights into the financial benefits of the proposed planning in this tool. An overview of the impact of the changes made in the drumbeat patterns compared to the previous period must be given.

1.5 Research Design

In alignment with the problem statement and the research question above, we formulate the main research question as follows:

> *"How can FrieslandCampina optimize costs between setup and inventory of the plant in Aalter by developing a tactical production planning tool using the optimal cycle stock levels and drumbeat patterns of all SKUs?"*

To answer the main research question, we formulate sub-questions that we answer throughout the research. These sub-questions are divided on a chapter basis.

Chapter 2: Current situation

In this chapter, we analyse the current situation in the plant in Aalter and explain the current steps of the production process and the steps used to obtain the tactical planning. Furthermore, by analysing the available data and the assumptions made earlier, we want to gain insight into the characteristics of the plant and evaluate the performance of the current tactical planning. In this chapter the following questions will be answered:

- What does the production process in the plant of FrieslandCampina look like?
    - Which method is currently used to calculate the optimal cycle stock levels and the optimal drumbeats of the SKUs?
    - What is the (financial) performance of the current tactical production planning?
    - What is desired and expected by the schedulers from the tactical production planning?

Chapter 3: A literature review

The following step is to dive into the literature to find suitable solution methods. First, we will focus on models to calculate the cycle stock levels and the drumbeats of SKUs. Next, we explain several planning problems and introduce different models describing this problem. We investigate the possibilities of models that include all aspects: calculating the cycle stock levels and drumbeats and constructing a tactical planning. Finally, we look at methods to evaluate and measure performance. This chapter will answer the following questions:

- Which methods found in the literature regarding the optimization of tactical production planning are suitable for this research?
    - Which methods are proposed in the literature to calculate the drumbeats (product frequencies) and the cycle stock levels for SKUs?
    - Which models are proposed in the literature to construct a tactical production planning as used by the plant in Aalter?
    - Which models are proposed in the literature to construct a tactical production planning including calculations of the cycle stock levels and the drumbeats?

Chapter 4: Model approach

In Chapter 4, we use the gained knowledge to discuss and implement planning methods to optimize the current situation. First, we determine what adjustments are needed to model our problem and what data we need for the model found in the previous chapter. Also, the assumptions are discussed and the specifications of how the model operates are given. The research questions to be answered in Chapter 4 are:

- How can we develop a tactical production planning model that optimizes the cycle stock levels of all SKUs?
    - What changes are needed in the chosen model to make it applicable to this case study?
    - Which data is needed and what can be used from the existing model?
    - What assumptions are necessary?
    - How does the model operate?

Chapter 5: Computational results

After the model has been properly designed, we can assess the performance of the model built. First, insights must be given to what extent the cycle stock levels and the optimal drumbeats have changed from the previous settings. The financial impact of the optimized tactical planning can be calculated and compared with the current situation. Furthermore, the performance of the tactical planning can be compared with the current situation and with the data from the existing model. Also, a sensitivity analysis will be done to see the impact of the chosen inputs and assumptions. The following questions will be answered in this chapter:

- How does the proposed planning tool perform?
    - How do we verify and validate our model?
    - To what extent are the optimal cycle stock levels and the optimal drumbeats included in the tactical planning?
    - What is the financial impact of the optimized tactical planning?
    - How well does the optimized tactical planning perform compared to the current situation?
    - How do the results change if one or more inputs/assumptions change?

Chapter 6: Conclusion and recommendations

In this chapter, we will discuss the final conclusions and recommendations based on our main research question. In addition, we give recommendations about the implementation of the tool within FrieslandCampina. We will answer the following questions:

- What is the answer to the main research questions?
    - How can this optimized tactical production plan be implemented in the plant in Aalter?
    - What recommendations can be given?
    - What further research options are recommended?

In Figure 4 we show the structure of answering the research questions that we discussed above. In the grey boxes at the bottom, you can see what methodology we use to achieve the desired result.

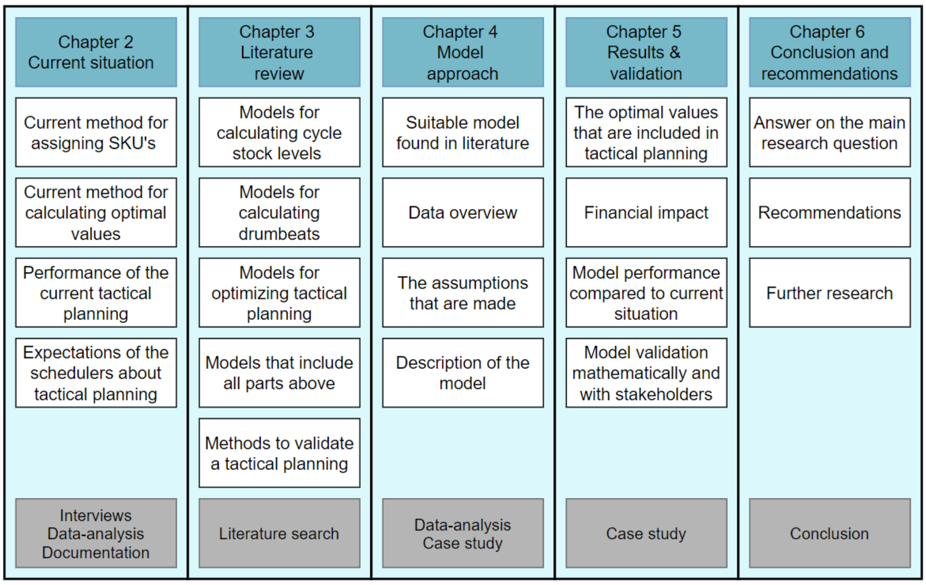

Figure 4: Research approach

1.6 Scope

This research considers all the SKUs that are produced in the plant of FrieslandCampina in Aalter. So, only the finished goods are part of this research. The stock of raw materials or packaging materials is out of scope and will not be investigated. The assumption is made that these raw materials are always on stock and will not influence the tactical production planning in this research. This is because these raw materials are only a fraction of the total stock value of FrieslandCampina.

As indicated earlier in the problem statement, the calculation of the safety stock is out of scope. FrieslandCampina is working on a promising tool that can be used soon. The calculations in this research will be based on the safety stock values as they are currently known. As soon as the updated safety stock values are available, the data will be updated with this new information.

Next, within the scope of this research, forecasting techniques will not be researched. Forecasting is done by the Demand Planning department that uses advanced tools. It will be very time consuming to fully comprehend these techniques and optimization is not expected to lead to significant improvement.

This research will focus on the tactical production planning of all SKUs. Operational planning activities, done by schedulers, are not part of this research. To obtain an optimal tactical production planning, the optimal cycle stock levels and drumbeat patterns must be researched in-depth and will likely be changed. For these calculations, more insight is needed into the inventory and setup costs.

The implementation of the tactical production planning is not included in the scope. However, we advise on what next steps should be taken and how an implementation of the results could be done. If the results are promising during the research and there are possibilities to implement the tactical production planning, we will take that change. The results of the implementation will be then discussed in this research too.

1.7 Deliverables

At the end of this research, we will deliver the following products to FrieslandCampina:

- A prototype of a tactical production planning tool including calculations of the optimal cycle stock levels and optimal drumbeats.
    - This will probably be a spreadsheet with a planning tool
- Insights in the financial impact of the proposed tactical planning

As stated above in the scope, the implementation of the tactical production planning is not included in the scope. However, when the results are promising and the time permits, the implementation will be done for one particular packaging line. The results of the implementation will also be discussed in this research.

2. CURRENT SOLUTION

This chapter describes the current situation as it can be found at FrieslandCampina. First, we describe the production process in Section 2.1, followed by the planning process in Section 2.2. In Section 2.3 we describe the cost drivers for this research. The capacity restrictions are explained in Section 2.4 and in Section 2.5 we discuss the shelf lives. Next, in Section 2.6 we give more insight into the current use of the drumbeat patterns and the earlier projects. In Section 2.7 we discuss the current performance measures used within the supply team. In Section 2.8 the desires of the manager, planners, and schedulers are mentioned, and we end this chapter with a conclusion in Section 2.9.

2.1 THE PRODUCTION PROCESS

In this section, we provide a high-level overview of the production process. It is not intended to outline the entire technological process, but to gain insight into the different steps to understand the production process of the plant. This will help to comprehend all the different constraints that must be considered during this research.

The products produced in the plant are divided into 3 categories, namely carton, plastic bottles and plastic cups. The plant produces around 400 different products on 17 packaging lines in total. Four of these packaging lines produce carton products, 10 packaging lines produce plastic bottles and the cups are made by 3 packaging lines. The figure below shows a few examples of the products.

Figure 5: Examples of SKUs

The production process starts with the farmers that deliver the milk to the plants of FrieslandCampina. These farmers have agreements about the amount of milk they are allowed to deliver. Some of these farmers are full members which mean that they can always deliver all the milk that they have available. Due to these agreements, it happens that the amount of milk delivered exceeds the production demand all over FrieslandCampina. This remaining milk is often sent to the plants where they produce cheese. The business group Consumer Dairy is only focused on profitable products. Therefore, they only receive the amount of milk that is necessary for the scheduled production. The allocation of the milk is done by the Milk Valorisation & Allocation (MVA) department. Because this allocation is based on the schedule made for production this process is pull-driven.

The milk that is allocated to the plant in Aalter is delivered at the site by tank trucks. The department O&D, which stands for *Ontvangst & Dispatch*, is responsible for collecting all milk and processing it into finished products. Besides the milk, there are other ingredients needed, for example, sugar and cacao. The materials for packaging the product must be available before producing, think of straws and caps. All these ingredients and materials are needed to be available before the production can start. When the milk arrives at O&D, the first step in the process is the pasteurization process. Within this process, the fat is separated from the milk to make skimmed milk. This is done by big centrifuges which spin the containers of milk at high forces. From the skimmed milk, they can make cream or every type of milk with each their own fat percentage with high accuracy. With the right type of milk, the finished recipe can be made. Some recipes do not require any other ingredients and will directly go to the sterilization process. Other recipes will be first mixed with other ingredients to obtain the right recipe. The required recipe is selected in the computer and the process starts automatically and ends with the correct end product. Regardless of the type of recipe made, it must be sterilized before it can be put into its packaging. Within this process, the recipe is heated above 100 ˚C which make sure all the bacteria are killed. That is why sterilized milk has a longer shelf life and is kept outside the refrigerator in the stores, also called ambient products. The sterilized recipes are moved to the aseptic tank which is connected to the packaging line. These aseptic tanks are free from contamination caused by harmful bacteria or other microorganisms. From these aseptic tanks, the products are filled with the right recipe and in the right packaging on a packaging line. One important constraint in this process is that some packaging lines are connected to the same aseptic tank. Table 1 shows an overview of the packaging lines that are present in the plant in Aalter and which aseptic tank is connected to each packaging line. Almost every packaging line has its aseptic tank, but some packaging lines do share their aseptic tanks. This makes it impossible to fill two different recipes on those packaging lines at the same time. Some of the packaging lines can fill multiple formats.

Table 1: Information about the packaging lines

Category	**Name of the line**	**Specification**	**Aseptic tank**
Plastic bottles	V	1 L	AT 7
	U	200/250 ml	AT 6
	T	500 ml	AT 5
	R	300/400/1,000 ml	AT 03
Carton	A	1,5 L	AT 21
	C	500 ml	AT 20
	E	1 L	AT 22
	F	1 L	AT 22
	G	200 ml	AT 23
	H	200 ml	AT 24
	I	1 L	AT 24
	J	1 L	AT 24
	K	1 L	AT 25
	L	1 L	AT 26
Cups	X	7.5/10 ml	AT 10
	Y	7.5/10 ml	AT 11
	Z	7.5/10 ml	AT 12

So, with the final recipe in the aseptic tank, the process of filling the packages can commence. Each packaging line starts with preparing the packaging material. At the carton packaging lines, a large roll of the carton is installed at the beginning of the packaging line. This roll is also delivered completely sealed so that the packaging is and remains sterile. At the first part of the packaging line, the carton is folded into the right format. Each package is filled with the correct amount of the corresponding recipe and the cap is placed on top of it. The next step is to laser the best before date on each packaging. Depending on the wishes of the customer, the single items are placed in carton boxes or a plastic sleeve is folded around multiple packages. At the end of the packaging line, a palletizer is used to place the multi-package on a pallet. If the pallet is fully loaded, a plastic foil is wrapped around it, and a label is placed on it. The moment the label is scanned, the pallet is no longer part of the plant but is registered in the warehouse. In the warehouse, the quality checks are performed and when approved the pallets are transported to the customer.

For the plastic bottles and the plastic cups, the steps are almost equal. The major difference is the supply of empty bottles and cups. The plastic bottles are made within the plant itself. There are small plastic spheres delivered and just before the packaging line, these bottles are blown. They try to make these bottles in advance. However, the packaging line can fill more bottles than the bottle machine can produce. With high demand levels, these bottles might get out of stock, but this situation is rare and therefore not taken into consideration. The plastic cups are delivered as a whole, and the major difference is the way these cups are filled and sealed. In the figure below we show the general steps from milk delivery until the moment the pallet belongs to the warehouse.

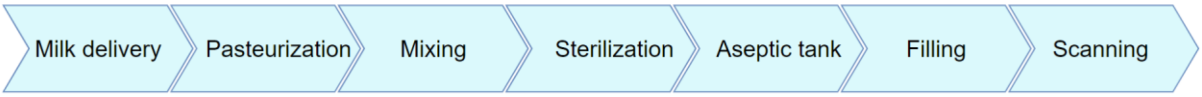

Figure 6: Production steps in the plant

2.2 THE PLANNING PROCESS

Before the production of products can start, an actual production planning must be available. In this section, we discuss the planning process of the plant with the relationships between various departments. The production plant in Aalter operates mostly according to the make-to-stock method to match the inventory with the anticipated consumer demand. This method requires an accurate forecast of the demand to determine how much stock is needed. First, we will explain the planning tools that are used by FrieslandCampina, which is necessary to understand the whole planning process. Next, the process from operational demand until production planning is described.

2.2.1 SAP

FrieslandCampina uses a real-time Enterprise Resource Planning (ERP) system, called SAP. This system makes it possible for FrieslandCampina to standardize and simplify processes, systems and data globally. All the information that is stored in SAP is called the *'masterdata'*. This data contains all information about each resource, SKU, packaging line, capacity and a lot more. Also, an optimization tool is integrated into this system, which can construct a planning towards optimality. SAP can combine all this information to make a production planning for all the RFC plants. In short, SAP does the main calculations and the planners can adjust manually if necessary.

2.2.2 Operational demand & production planning

The plant in Aalter operates according to the make-to-stock method. This means that the production planning is based on the forecast made by the demand planners. The process of operational demand & production planning (OP&PP) all starts with the forecast made by the department of demand planning. Figure 7 shows the process flow of all steps described during this process. Each demand planner has insight into the portfolio of each customer. Based on historical data and additional information of the customers they can make a forecast per customer in SAP for the next 18 months. Customers must inform FrieslandCampina about their planned promotions, so this information is always integrated into the forecast.

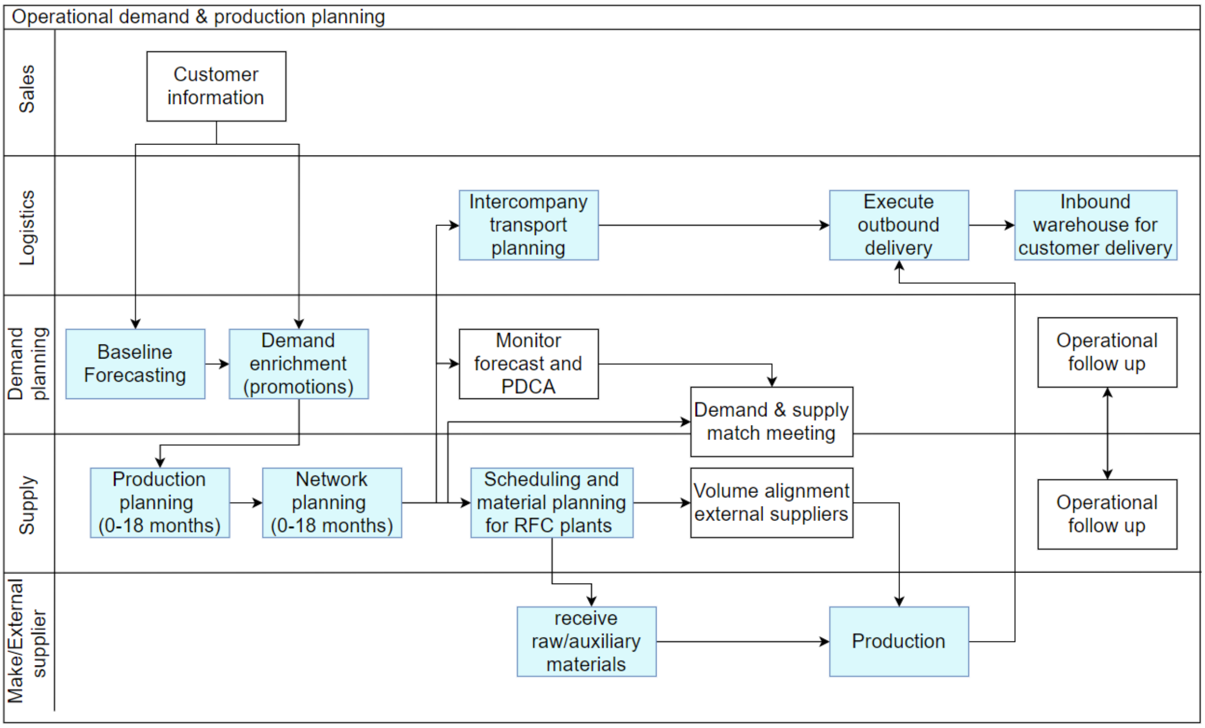

Figure 7: Operational demand & production planning (process flow)

The demand planners are working on the forecasts each Thursday and Friday. Over the weekend the Advanced Planning & Optimization (APO) tool integrated into SAP constructs a production planning covering the next 13 weeks. This planning is mostly based on the following information:

- forecast of 18 months per SKU made by the demand planners;
- drumbeat patterns per SKU;
- stock on hand.

The planning that is made for the upcoming 13 weeks contains the quantity of each SKU that must be produced in each of those 13 weeks. On Monday morning the supply network planners (SNP) start with checking the planning that is made by APO in the weekend. This is necessary because APO plans according to an unconstraint method, which means that the planning can exceed the available capacity. It is their task to make sure that there is no out of stock in the planned horizon and that the capacity constraints are not violated. With an Alert Monitor, the critical points are highlighted, so they do not have to go through all SKUs manually. Where a demand planner sees the total portfolio of a customer, an SNP has only insights into the total forecasted demand per SKU. According to this production planning, the Material Requirement Planning (MRP) is created by the material planners. They are responsible for receiving all the raw materials and packaging for production on time.

The 13-week planning made by SNP is ready each Tuesday afternoon. Wednesday morning the schedulers start with the detailed planning in the planning tool OMP which is connected to SAP. The detailed production planning includes the days left of the current week and the next two weeks. The current and next week were already scheduled last week, but some changes can be made if necessary. The second week must be scheduled according to the information from the production plan made by SNP. On Thursday and Friday, the demand planners are working on the forecast again. This cycle is repeated weekly. The separate operational follow-up, as shown in the picture, is needed to address the day-to-day operational issues and to take appropriate actions if necessary.

It is important that the demand and supply planners are aware of each other's information and that their information is aligned. Therefore, there is a demand meeting and a supply meeting every week. In a demand meeting, the forecast is discussed and approved. In a supply meeting, the planning for the plant discussed and approved. If they see already some bottlenecks or other problems, they try to come up with several scenarios and solutions. In a monthly Pre-Sales & Operations meeting, these problems with the corresponding scenarios are researched and discussed. A few days later, in the Sales & Operations meeting, the best scenario is chosen, and the actions are determined. In this meeting, the forecast is officially approved, which means that the production quantities are officially known. This cycle of meetings repeats monthly to keep track of all the developments in the whole process from plant to customer.

2.2.3 Sales order to cash

The products that are produced must be sold to customers. This process is called sales order to cash and starts with a sales order of a customer. There are two different ways an order can be placed at the Customer Care team. First, a request in any form is placed by the customer for the desired products. The other way is according to the business model Vendor Managed Inventory (VMI). Within this way of working, all the information is given to FrieslandCampina and they are responsible for maintaining an agreed inventory of the SKUs at the customers' location. Using this model, FrieslandCampina checks the inventory and makes decisions if any products are needed to send to the customer. The orders are picked, an invoice is sent, and the products will be delivered.

Customer Care is also responsible for the service questions and complaints of the customers. The task of the Supply team is to inform out of stock of products as soon as possible. When short-term out of stock is expected, Customer Care communicates this with the customers. Through this proactive attitude, they try to limit the consequences for the customer by taking appropriate measures. When a long-term out of stock is expected, this is communicated to the Demand Planning department. They are responsible to communicate this with the internal stakeholders. In the demand and supply meetings, these problems will be addressed, and appropriate actions are taken.

2.3 Cost drivers

It is a natural approach trying to keep the total costs as low as possible over all processes. The main cost drivers for the plant in Aalter are the setup costs and the inventory costs. There is an optimal balance between these costs, but this trade-off is difficult to determine. If the plant uses large production batches, this would result in low total setup costs as fewer changeovers and CIPs are required. But this will result in high inventory costs to store all the products made to stock. On the other hand, if many small batches are used in production, the total inventory costs will be low because not many products are produced to stock. But this will result in high total setup costs because a lot of changeovers and CIPs are required due to the small batch sizes.

To make this trade-off, the setup and inventory costs must be determined. However, determining these costs is a hard part of many operations. While determining these costs in our research many assumptions and estimations are made. Therefore, we must execute a sensitivity analysis at the end of our research. In the following two sections, more insights are given in how we estimate these cost drivers.

2.3.1 Setup costs

The setup costs are difficult to determine because these costs are sequence-dependent and different for each packaging line. The setup costs are made when the packaging line must shift from one SKU to another. Depending on the sequence of the SKUs the packaging line and the aseptic tank must also be cleaned, which is called Clean-in-place (CIP). A CIP refers to the automatically cleaning that is done without dismantling parts of the packaging line. Whether a CIP is needed depends on the recipe of the subsequent SKU that must be produced. However, in this research, we focus on optimizing the tactical planning of the plant in Aalter, which does not include the daily planning in which the order of the SKUs is determined. But without knowing the sequence of operational planning we do not know if a setup is necessary and if we should charge the setup costs.

In Chapter 4 we explain in detail how we overcome this problem. In short, we translate the dependent setup costs into costs at different levels. We distinguish between product family level, recipe level and format level, so for each level, we must determine these setup costs. In a product family, we combine SKUs which do not need a setup one after another. These are made based on the matrices available stating when a CIP is needed and if there are any special details to consider. Figure 8 shows a snapshot of these matrices. The diagonal will always be blanc because no CIP is needed when the same recipe or same recipe family is produced next. The numbers refer to the different recipes and it is known from other data which recipe is required for which SKU.

				MELK					VERRIJKTE MELK
	van		naar	903397 903398 903399 903400	903393 903394 903395 903396	903459	903401 903402	903460 903461	903479
				Weidemelk (Ned oorsprong)	Weidemelk (BE-Nl)	Weide (BE)(VM/HV) met vit. D (geen claim	AA-Weidemelk BE	AA-Weidemelk BE + vit D (Campina-	HV+Ca+MCC +Vit.D
MELK	903397	Milk Meadow Whole 3,5% Fat Mix NL	Weidemelk (Ned oorsprong)			CIP	CIP	CIP	
	903398	Milk Meadow Ssm 1,5% Fat Mix NL							
	903399	Milk Meadow Skimmed 0,1% Fat Mix NL							
	903400	Milk Frothing 4% Fat Mix							
	903393	Milk Whole 3,5% Fat Mix	Weidemelk (BE-Nl)	CIP		CIP	CIP	CIP	
	903394	Milk Ssm 1,5% Fat Mix							
	903395	Milk Skimmed 0,1% Fat Mix							
	903396	Milk Cappuccino 4% Fat Mix							

Figure 8: Snapshot of the sequence matrix

As said, we distinguish setup costs on three different levels. First, at the product family level where we charge the costs of a CIP when switching to SKUs from another product family. For a standard CIP, they take into account 4 hours. When a CIP takes place, not only the packaging line is cleaned, but also the aseptic tank and the sterilizer. As we showed in Table 1, there are many different aseptic tanks, each with its own sterilizer. To be able to determine the costs precisely, we create different subcategories and tried to estimate the costs for the packaging line, the aseptic tank, and the sterilizer. The costs of these subcategories are given in Table 2. The costs of cleaning the packaging line, the aseptic tank, and the sterilizer are estimated between €82 and €248. Next, all three parts must be sterile and to do so, different chemicals and energy are needed. During a CIP no employee is full-time needed, but only for some of the steps, someone is required. Also, the cleaning materials and other aspects of product loss are never estimated in detail together with several Technology Specialists.

Table 2: Total costs of CIP

Subpart	Costs
Cleaning: Chemicals and energy	
Sterilization: Chemicals and energy	
Employees	
Fills loss	CONFIDENTIAL
Phase separation	
Sealing	
Ramp up	
Total CIP costs	

Second, we charge setup costs for a changeover at the recipe level. When we switch from one recipe to another, the packaging line should at least be flushed with water and adjustments could be necessary to the packaging formats. For such a changeover 40 minutes are taken into account. No detailed research is ever done to determine the costs of these changeovers. Due to the detailed research, we have done on the costs of a CIP, we use these to estimate the costs for a changeover. A CIP takes four hours and a changeover only 40 minutes, so for the changeover, 16.7% of the CIP costs are taken into account. This is a rough estimate, but no data is available on the costs of a changeover.

When we look at the setups done in five random weeks, we see a clear difference between a CIP and a changeover of 40 minutes, see Table 3. In 72% of the setups, only a changeover is required. Due to this big difference, it seems important to take the different options into account while modelling.

Table 3: Overview of the number of CIPS and changeovers per week

Weeks	# 40 minutes	% 40 minutes	# 240 minutes	% 240 minutes
2021W4	66	66 %	34	34 %
2020w49	54	75 %	18	25 %
2020w46	70	70 %	30	30 %
2020w33	57	75 %	19	25 %
2020w14	74	75 %	25	25 %
Average	**64**	**72** %	**25**	**28** %

The last setup we consider is for five packaging lines that can produce multiple product sizes. The time consumed for converting a packaging line from one format to another varies widely between 0.25 and 9 hours, so the associated costs also differ a lot. This is less expensive than cleaning a packaging line, but employees are necessary for converting the packaging line and production time is lost. Multiple conversions of the packaging line in a week is not beneficial. Again, no data is available about the costs of format changeovers. Therefore, we analysed the number of employees that are required for a changeover and multiplied this number with the time and the costs of an employee.

A combination of these three options may be required when switching from one SKU to another. The action that takes the longest will determine the time it takes to switch to the next SKU. However, because we do not focus on the specific order, we always take the time and the cost of all actions into account. This will lead to higher setup costs than in reality, but these savings can be realized by the schedulers at the operational level.

2.3.2 Inventory costs

The other cost driver is the inventory costs. The inventory costs often exist out of three main parts: the holding costs, the cost of capital and the costs of risk of obsoletes (Durlinger, n.d.). In this section, we explain how we estimated these three cost aspects to determine the inventory costs for all SKUs.

The products that are made in the plant in Aalter are stored in different warehouses in different countries depending on the destination of the product. The hard part about allocating the holding costs is that SKUs are always stored for a few weeks in Aalter and then sent to their destination, which varies per order. The level of detail of the model will increase a lot if we included the destinations of each SKU per order. To overcome this problem, we analyse the inventory of the past years to come up with an average holding cost per SKU.

In 2019 FrieslandCampina started tracking their stock on the SKU level. This file keeps track of the value of an SKU in a particular or multiple warehouse(s) at the end of each month. This information tells us how much of a certain SKU in euros is stored in which warehouses. This allows us to calculate per SKU and per warehouse how much stock there is on average in euros. Using the costs of goods sold we can convert this to the number of FILLs. This means how many items are in stock on average per SKU per warehouse. Knowing the average amounts per warehouse we need to know the prices per warehouse to hold stock. This is where we reached to the financial specialist of CSC NL. The financial department has made an ABC report of the warehouse's costs of the year 2020. This is a very detailed analysis in which they determined the cost per pallet for 20 days. The most important aspects that they included in their analysis are personnel costs, operating leases and rents, automation costs, utilities, facility management, repair & maintenance, depreciation & amortisation, transportation & cleaning and office costs. They assigned a percentage per warehouse to each aspect based on the financial statements, the stock values, and the realized costs. With these percentages, the actual costs, and the stock levels they calculated a holding price per pallet for 20 days per warehouse, see Table 4.

Table 4: Location and prices of the warehouses

Country	**Location Warehouse**	**Price full pallet per 20 days (€)**
The Netherlands	Maasdam	
	Rotteram	
	Waddingxveen (Nedcargo)	
	Nuenen	
Belgium	Aalter	
	Bornem	CONFIDENTIAL
	Willebroek (TDL)	
	Lummen	
Germany	Heilbronn	
	Köln IL	
	Köln WL	
England	Wolverhampton	
	Milton Keynes	

Together with the Supply Network Planner, we gathered the information about the number of SKUs on a pallet. We can convert the number of FILLs calculated per warehouse into the number of pallets. We also convert the price per pallet per 20 per warehouse into a pallet price per day per warehouse. Per SKU and per warehouse we multiple the price per day per pallet with the average number of pallets stored. Finally, we take the sum of the weighted average to come up with an average holding price per SKU. This holding price is different for each SKU and is based on multiple assumptions. This estimation is mostly based upon information of 2020, which is not representative due to the COVID Pandemic. Therefore, we must do a sensitivity analysis at the end of this research.

Next to the holding cots for the SKUs, we take the Weighted Average Cost of Capital (WACC) into account. This component is often referred to as the capital costs of a company. The WACC depends on how a company is financed and is determined by the Control Department. For FrieslandCampina the WACC value for Europe has been set at 4%. The WACC value is a measure of capital, which averages the costs of debt and common equity. We calculate the weekly cost of capital by multiplying the WACC weekly rate with the cost of one pallet and the weekly inventory level in pallets.

The costs arising from the risk of obsolescence are not included in this research because the products produced in Aalter are ambient products and therefore this cost factor should be zero. The golden rule is that the production of ambient products is well assigned and will not result in any waste at all.

The inventory costs per SKU is the holding costs per pallet plus the costs per unit time for storing end-products divided by the number of SKU per pallet. This results in an inventory cost per FILL per day per SKU. For the model, these values can be converted into weekly inventory costs by multiplying with seven days.

2.4 Capacity restrictions

The total capacity of the plant depends on a lot of different factors. The plant has a limited capacity which is regulated by demand planners, supply network planners, schedulers and production managers. In this section, the aspects that influence this capacity are discussed in more detail.

2.4.1 Technical aspects

The plant in Aalter is a complex factory with a lot of restrictions. There are so many constraints to consider that not even all planners and managers are always aware of all these constraints. These constraints can be split in relevance for the short-term planning and the long-term planning which has the focus in this research. For the short-term planning, constraints as the availability of the different types of milk at the plant in Aalter are considered. Some recipes can be made from all four kinds of milk, but some recipes are limited to one type of milk. The production depends partly on the delivery of each type of milk. Besides, the milk must be mixed and filled after delivery within a certain time. The details of these constraints are complicated but known by the schedulers and are more relevant on a weekly level. Therefore, for this research, this constraint is less important.

The constraints which influence the long-term planning are important for this research. One of those constraints is about the aseptic tanks. As mentioned before, the packaging lines are connected to aseptic tanks but not every packaging line has its aseptic tank, so two recipes cannot be filled on the packaging lines connected to the same aseptic tank. This information is already given in Table 1.

Another important constrain is production batch sizes. The size of each batch is based on the schedule that has already been created. However, this batch size will always be increased a bit due to the loss during the entire production process. The same batch size is used during the entire production process. The desirable minimum production quantity differs between 30,000 litters and 200,000 litters of a certain recipe. If the desired batch size is below this minimum the schedulers try to schedule this

SKU together with another SKU that has the same recipe. If this is not possible, it is reported to the demand planners to decide if the production needed and start production with the minimum batch size, with a high chance on wasting part of it. The other choice is to take the risk of going out of stock and report this to the customer in advance. The maximum quantity for all recipes for each week must also be considered. This is because of several reasons, but for example, the production of cream is very slow. Therefore, it becomes impossible to produce cream whole weeklong because the packaging lines can fill much faster and will often have to wait for the production of cream. It is important to match the production planning with all steps in the whole process of the production plant.

2.4.2 Manning

The capacity of the packaging lines depends on the available personnel in a given week. The plant works with 3 shifts in 24 hours with the following timeslots: 06:00 - 14:00, 14:00 - 22:00, and 22:00 - 06:00. When the plant is operating 24 hours and seven days a week, there are 21 shifts available. However, they try to schedule all production between Monday 06:00 and Friday 22:00, which means that there are normally 15 shifts available. The number of shifts needed are monthly reviewed and can be changed at any time. In the plant, all packaging lines can run at the same time, but the availability depends on the availability of personnel.

2.4.3 Overall Equipment Effectiveness

Another important variable for the production capacity is the Overall Equipment Effectiveness (OEE) of every packaging line. The OEE measures the performance of the equipment in a factory. The OEE is calculated by dividing the net time during which the packaging line actually produces an acceptable product by the actual number of hours that the equipment is expedited to work (Schiraldi, 2013). The calculated percentage indicates whether the packaging line is doing what it is supposed to do. The time it takes to switch between SKUs is an event that stops production and lowers the OEE of that packaging line. The OEE is closely connected with two other variables; the speed of the packaging line and the loss factor. The speed of de packaging line is fixed and is different per packaging line and depends mostly on the format of the packaging the must be filled. The loss factor indicates the time that is used for routine stops and is calculated by the fixed production speed and the chosen OEE:

$$Loss\ Factor = \frac{Production\ Speed - OEE}{Production\ Speed} * 100$$

When a packaging line has a capacity for 100 hours with an OEE of 80%, production is only planned for 80 hours. The time remaining is needed for changeovers, minor defects and other downtimes. Each packaging line has its own calculated OEE percentage. The goal is to achieve the highest possible OEE. Every month the performance is closely monitored and the OEE of each packaging line is assessed. Figure 9 provides a snapshot of the OEE values several weeks of 2020 of packaging line F.

Figure 9: The OEE values of 13 weeks and the target value

		week														line (OEE)	avg 4 wks	avg 13 wks	plan	Budget OEE 2020
Aalter	Effectieve tijd (OEE)	F - KARTON	64	74	61	56	51	54	69	63	58	59	51	70	#N/A	Karton - F		#N/A	65%	63%

According to these performances, the decision can be made to adjust the planned OEE value in SAP. If the performance of the OEE is lower in the past four weeks, the OEE will be adjusted downwards. This is necessary because apparently too much production is scheduled on that particular packaging line. However, if the OEE has been consistently lower in the past four weeks, the OEE is adjusted downwards but extensive research will be conducted into the cause. The goal is to achieve the highest target OEE, so if issues arise that negatively affect the OEE, action is taken. If the OEE percentage is significantly higher in the past four weeks, the OEE can be increased. This means that there is too little planned on that packaging line. Still, improvements can be made, and these options are also discussed to achieve an even higher OEE.

2.4.4 Maintenance

Another variable for the capacity of the packaging lines is the maintenance that is needed in every production plant. This is planned in advance and is automatically registered in SAP. There will be no possibility to schedule any SKU on that particular packaging line when maintenance is carried out.

2.4.5 Public holidays

Public holidays are also included in SAP and no production is performed on these days. As with maintenance, no production can be planned. However, it now applies directly to all packaging lines throughout the whole factory. The advantage is that these days are known in advance, but the disadvantage is that these cannot be adjusted.

The manning, the OEE, the planned maintenance, and the planned public holidays all directly influence the capacity of each packaging line. The total capacity of a packaging line is calculated in the number of hours available for production in that week. With the given speed of a packaging line, the quantity of production planned is converted to the required hours. Figure 10 provides a snapshot of APO which shows the capacity and the planned hours on packaging line *'F'* for the first weeks of 2021. The capacity consumptions show the hours that are currently planned for those weeks. The grey row at the bottom indicates the percentage that has been filled for that week. If 100% is exceeded, the responsible SNP will receive a warning to manually spread the production or to increase capacity.

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Figure 10: Snapshot of the available capacity of packaging line F

2.5 Shelf lives

Every SKU has an assigned shelf life in days, which indicates how long a product may be stored before its quality deteriorates. This is equal to the best before date lasered on each package. In addition to this shelf-life, FrieslandCampina must especially take into account the *required minimum shelf life*. This is the minimal number of days before the best before data expires that the customer accepts. So, if the shelf life of a product is 200 days and the required minimum shelf life is 120 days, the product must be on the shelves of the customer within 80 days after production. When products are not sold within their minimum required shelf life their value decreases. When this happens, they may be sold at a discount, given to the food bank or destroyed completely. The total shelf lives in months of all SKUs produced in the plant in Aalter are depicted in Figure 11. The average shelf life of all SKUs is around seven months, while the average required minimum shelf life is four months. That means that on average the products must be at the customers' location within three months after production and must be consumed on average within seven months after production.

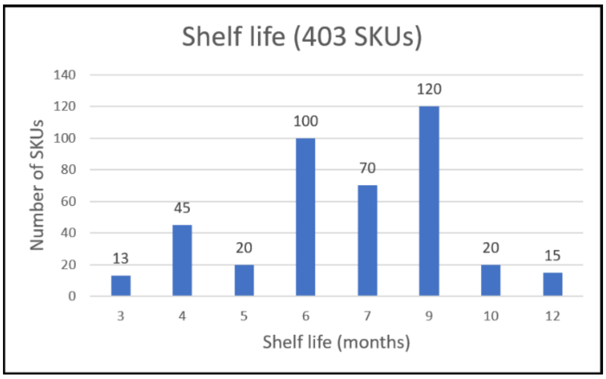

Figure 11: Shelf lives SKUs

2.6 THE USE OF DRUMBEAT PATTERNS

FrieslandCampina uses the so-called drumbeat patterns in the production planning. In this section, we dive deeper into what these drumbeat patterns are and why they are needed. We explain their purpose, the current method by which the drumbeat patterns are currently calculated, and the proposed model that is developed at the beginning of 2020 is discussed. Also, the drawbacks of the current use of drumbeat patterns are discussed.

2.6.1 The purpose of the drumbeats

The planning for the upcoming 13 weeks is made by the planning tool called APO according to an unrestricted method. This means that the capacity constraints are not considered. Therefore, APO could schedule all the SKUs in the same week, as it does not take into account the plant's capacity in that week. To obtain a more accurate planning, FrieslandCampina came up with drumbeat patterns for each SKU. These drumbeats patterns are stored in SAP and are part of the 'masterdata'. These drumbeat patterns make sure that APO knows which week to plan which SKU. For each SKU that is made in the plant in Aalter, a specific drumbeat pattern is determined. Regardless of the seasonality for a large number of SKUs, the drumbeat patterns are fixed throughout the year. Therefore, the production quantities fluctuate a lot and sometimes manual adjustments are necessary. The drumbeat patterns are made of 4 digits consisting of a combination of ones and zeros. The four digits represent four weeks in which the one stands for production and the zero for no production in that week. There are 15 different combinations possible of which 12 combinations are currently in use. The table below shows an overview of the current drumbeat patterns for the SKUs of the plant.

Table 5: Drumbeats for all SKUs

Production every x weeks	**Drumbeat**	**Total SKUs**
1	1111	48
2	1010	75
	0101	60
	1101	1
	0111	10
3	1001	4
	0110	5
	0011	6
4	1000	66
	0100	31
	0010	33
	0001	45

The different combinations are used to distribute the volume over different weeks. If all SKUs that are scheduled every four weeks would have the drumbeat pattern *1000*, all SKUs will be scheduled in the same first week. Due to these combinations, these SKUs are spread over the weeks. The drumbeat pattern of production every three weeks is not often used because its repeating pattern of these odd weeks is difficult. The first production is in week 3, but the next production is in week 6. This means that the production of every two and four weeks coincides with other products. This is the reason why they prefer to plan the SKUs with repetition every week, every two weeks or every four weeks.

2.6.2 Determination of the drumbeat patterns

The drumbeat patterns are used for a very long time and a lot of SKUs are introduced and removed over the years. The drumbeat patterns of all SKUs were last revised in 2015 with a project aimed at revising the drumbeat patterns of all SKUs. This revision of the drumbeat patterns was largely based on common knowledge and logical thinking rather than mathematical calculations. The main reason for this choice is that there are so many constraints that must be considered to arrive at a feasible solution, which makes it difficult to perform mathematical calculations. However, this approach is likely to lack major improvements which are more likely with a mathematical approach. In this project, the determination is done in several different steps and will shortly be described. First, they investigated the SKU portfolio and defined the production frequencies for all SKUs. The division of these production frequencies was based on the minimum batch size and is shown in Table 6.

Table 6: Classification of the production frequencies of the SKUs

Classification	**Production every x weeks**	**Measurement**
High	1	Average week volume > Minimum batch size
Middle	2	Minimum batch size > average week volume > (Minimum batch size /2)
Low	4	Minimum batch size > average week volume > (Minimum batch size /4)
Minority products	Random	-

This is a straightforward method to determine the production frequencies. The next step was to determine the actual drumbeat patterns and how to spread the SKUs equally over the weeks. To do so, the SKUs were divided into three flows: coffee milk, white milk, and flavoured products. For each flow, the biggest bottlenecks were determined. Combinations are made between SKUs to make the constraints visible for each flow and a planning is made based on the average volumes for each flow. This planning is discussed with production to find a solution that is also feasible in every step of the production. This process is repeated several times to end up with a feasible solution for the plant. When the planning for the combinations is made, a more detailed level can be investigated to optimize the planning even more. It was said that these drumbeat patterns would be evaluated every 6 months, but in practice, this did not happen.

Currently, the process of introducing a new SKU is as follows. If the recipe is already made in the plant for other SKUs and only the packaging is different, the drumbeat pattern will be equal to the SKUs with this same recipe. When a new recipe is introduced, they choose the week with the fewest different recipes to insert this SKU. Most of the time they start with production once every four weeks and increase if necessary. Currently, there is no mathematical support for determining the drumbeat pattern for new SKUs. So, in recent years many SKUs have been assigned and removed and therefore the revising the drumbeat patterns could lead to more efficient use of the plant.

2.6.3 Proposed new method

Due to the manual drumbeat pattern revision described above, FrieslandCampina wants to recalculate the drumbeat patterns with a mathematical model toward optimality. At the beginning of 2020, FrieslandCampina worked on a new model to recalculate the drumbeats. The goal of this model was to review the current drumbeat patterns, calculate new ones based on updated information and calculate the financial impact. Unfortunately, the model was not implemented because there was not enough support from the management team. This is mainly because the determination of the cost was unfounded, and no major financial progress could be made. However, a good start has been made as the basis for our research. Therefore, we briefly describe the model made by FrieslandCampina.

The model was only focused on the packaging lines 'E' and 'F' with the associated SKUs that are produced on that packaging line. These packaging lines are identical and connected to the same aseptic thanks. A lot of information is collected about these packaging lines on which 23 SKUs are produced. The determination of the drumbeats is done in several different steps. The first step in the model is calculating the optimal number of productions per year for each SKU. To perform these calculations, a trade-off is made between setup costs and inventory costs. This could result in production every 10 weeks for a certain SKU to achieve the lowest costs. The model uses the economic batch quantity (EBQ) method to make this trade-off and to calculate the new production frequencies. This is a measure to determine the optimal order size of a production batch that minimized the total cost. The EBQ is similar to the Economic Order Quantity (EOQ) but is called EBQ because there are no orders placed but batches are produced. The formula of the EBQ that is used in the model is as follows:

$$EBQ = \sqrt{\frac{(2 * Annual\ Demand * Setup\ Costs)}{Annual\ Holding\ Costs}}$$

This formula gives the optimal production quantity and by dividing this by the annual demand the number of productions per year is given. However, as described above, the shelf lives of the SKUs must be taken into account during these calculations. The shelf life of an SKU can conflict with the calculated number of production runs per year. These differences need to be checked for each SKU and in some cases, the number of productions per year needs to be increased, which directly increases the production frequency. Instead of producing an SKU every 10 weeks, the production should be every 6 weeks to make sure that the SKU does not automatically exceed the required minimum shelf life before a new production run is started.

The last step done in the model is calculating the financial impact of the new proposed production frequencies. This is simply done by calculating the setup costs and inventory costs with the new calculated production frequencies and compare this to the old situation. There are no other performance indicators taken into account while analysing this new proposed model. The reduction of the total costs due to the new production frequencies is presented in Table 7. This is a reduction of 4.6% of the total costs for the plant in Aalter.

Table 7: Reduction with the new model

Variable	**Old situation**	**New situation**	**Savings (%)**
Setup costs	CONFIDENTIAL		**6%**
Inventory costs			**2%**
Total costs			**5%**

The managers question whether the information collected for this model does indeed correspond to reality. Moreover, it is doubtful of these slightly easy calculations are a good reflection of the complex reality of the plant. The managers considered it too risky to continue with the model at that time. They decided to stop this attempt to find optimal drumbeats for the production plant in Aalter.

After calculating production frequencies, the next step would have been to determine the actual drumbeat patterns. This means that all SKUs with the correct number of productions must be distributed over the different weeks concerning all constraints. Currently, the drumbeat patterns represent only four weeks, but this is not a requirement. This division is quite hard because all the different restrictions of the plant and all the characteristics of the SKUs must be taken into account. When this is done correctly, it is possible to reduce the costs even more. This could be done by scheduling the same product families in the same week with the same repetition to reduce the setup costs. While determining the drumbeat patterns, all the technical aspects must be taken into account. A couple of these restrictions are already discussed above, but more information is needed to make an optimal and feasible tactical production planning. All the processes and steps in the plant are closely connected and this is what makes it complicated. Knowing all these details is almost impossible and therefore it is important while determining the drumbeat patterns to stay in close contact with the schedulers. They are working for many years in the plant in Aalter and are aware of all the restrictions. They are willing to help during this process to obtain a feasible tactical production planning.

2.6.4 The drawback of the current situation

There are some drawbacks of the current use of the drumbeat patterns in the plant in Aalter. Because it is such a complicated production process it is hard to determine the drumbeat patterns concerning all the constraints in the process. The way that the setup costs are included is questionable because the averages of these costs are included. However, depending on the distribution of the SKUs over the different weeks, the number of CIPs and changeovers is very fluctuating. It would be interesting to see how often the different combinations occur and take this into account when calculating the setup costs rather than averaging these costs. Optimizing these combinations per week would probably have a beneficial effect on reducing the setup costs even more. Therefore, it is desired to include the step of assigning the SKUs to the weeks in a certain planning horizon.

Furthermore, the model does not take into account any capacity restrictions. No check-up is done if the calculated drumbeat patterns would be feasible to include in the actual planning for the plant. An important step for obtaining the actual drumbeat patterns for the SKUs would be including the capacity restrictions of the plant. Moreover, it would be valuable if there would be a connection between the SKUs to minimize the number of CIPs, to decrease the possibility that the minimum and maximum production quantity is not met.

Another major drawback is the fact that the drumbeats are fixed and do not respond to seasonality. The only exception is Chocomel, for which the production frequency increases from August until January. The drumbeat patterns for these SKUs are manually adjusted. However, more products behave differently during different seasons. Due to the fixed drumbeat patterns and the fact that APO plans unconstrained, the planned quantities are fluctuating. This seasonality can be taken into account while determining the drumbeat patterns and especially by revising the drumbeats several times a year. This could be done to run the model or do the calculations more often with updated data.

A drawback of the proposed model concerns the inventory costs that are calculated per pallet per SKU. No information is used about how long certain products are actually stored in a warehouse. This duration differs per SKU and could be interesting to include in the calculations. Also, the rule of thumb used to include the risk cost should be reviewed to see if this has the desired result. Researching the setup and inventory costs for the plant in Aalter has started well, but improvements are still possible on several components.

2.7 Performance of the tactical production planning

It is important to measure the performance of the tactical production planning to draw meaningful conclusions about the proposed approach. To measure the performance of a planning several indicators are used. Every week in the supply team meeting the performance of the plants in Aalter, Bornem, Maasdam, and Rotterdam are discussed. This data is updated every Tuesday morning and the root causes for performing below target are discussed and actions are taken. However, the performance indicators used can only be calculated after production has taken place. This makes it difficult to use these measures to determine the performance of the planning created by the proposed model. To determine the performance of the proposed model, we focus on the costs of the plant and the inventory levels. Additionally, the number of changeovers per week and the distribution of the production of SKUs throughout the weeks could be a proper performance measurement.

The financial impact could be calculated before production takes place. This is also done in the proposed model at the beginning of 2020. A comparison is made between the total costs before and after the adjustments to the production frequencies. The total costs are split into the setup costs and the inventory costs. These will also be taken into account during this research. Also, routine stops can be measured before production takes place. If the new proposed planning requires fewer CIPs and changeovers, it would result in lower setup costs. However, it is important to take the inventory into account to say something meaningful about these analyses.

There are no performance measurements for the long-term production planning that SNP made for the upcoming 13 weeks. This schedule changes every week and only the first weeks of this planning are very accurate. Week 10 in this planning is only fixed in 8 weeks when it is sent to the schedulers. Therefore, the performance of this planning is not tracked. However, some SNPs track their performance by writing down when adjustments are made. In this way, it can be shown how many changes are needed to make the production planning for 13 weeks for the portfolio of this planner.

2.8 Desired by the planners & schedulers

In the subsection *Research goal,* the ultimate goal of the plant in Aalter is already shortly described. In this subsection, we dive deeper into the wishes of the managers, planners, and schedulers for the plant Aalter and especially why this goal is so important. Ultimately, they would like to have a tool that they can use to calculate the drumbeat patterns for a specified upcoming period. This period can be a quartile, which means that the drumbeat patterns must be revised every 3 months.

The tool would consist of several steps to obtain the desired result. First, the production frequencies are calculated taking into account the constraints of the plant and each SKU. Think of including the costs of the plant as well as the best before date, such that the proposed production frequencies are feasible. These calculations have to make a good trade-off between the setup costs and the inventory costs to minimize the overall costs in the plant.

The next step is to construct the actual drumbeat patterns. This means distributing the SKUs evenly over the weeks by taking the constraints into consideration. The hardest part is to take the constraints of each SKU and all the processes into account. This would result in a clear overview of each packaging line with the corresponding SKUs and their drumbeat patterns.

The final step is to include an overview of the financial aspects of the new proposed tactical planning. Not only the overall setup and inventory costs could be present but also the financial impact of each SKU if necessary. This could be very helpful for the schedulers, who often receive the question to reschedule but they are not aware of the financial impact of the decisions that they must take. Making these decisions based on a model where they can see the consequences of a certain decision makes it way easier to respond to such questions.

Moreover, for the Supply Network Planners, it would be a useful tool. With the appropriate drumbeat patterns, APO could make a more appropriate production plan for the 13 weeks horizon. In turn, this will lead to fewer adjustments that they have to make to achieve a feasible planning. Time would be saved using a tool that constructs the drumbeat patterns every six months. It would also be very helpful to have such a tool for implementing new SKUs in the planning. The data of this new SKU could be inserted in the model and the new drumbeat patterns, including the new SKU, could be calculated and inserted in SAP. No more gut feeling but real mathematical calculation to support the planners.

2.9 CONCLUSION

In this chapter, we answer the sub-question: "*What does the production process in the plant of FrieslandCampina look like?".* We gathered all relevant information that is required to describe the (problem) situation at the FrieslandCampina plant in Aalter. The current way of calculating the drumbeat patterns is not approved and therefore requires research to develop a good method with an even better solution. The drumbeat patterns are important to make sure that APO, knows in which week to plan each SKU. The determination of the currently used drumbeat pattern was done a couple of years ago and was mainly based on logical thinking rather than mathematical calculations. A new promising model was made at the beginning of 2020 but did not have the desired results.

Our research focuses on determining the right drumbeat patterns while minimizing the setup and inventory costs. The setup costs are sequence-dependent. In addition, the setup costs and setup time between recipes are higher than between SKUs with the same recipe. The inventory costs must be included and calculated for each SKU. The constraints will be specified during the modelling phase, but an important aspect is the capacity of the packaging lines. There is a limited capacity on the packaging lines each week. The bottleneck of the plant is the mixing of the recipes and therefore the capacity is also limited to the volume of each recipe that can be produced each week.

Given the above observations, we conclude that we should build a realistic model considering all identified cost components. We must try to incorporate as many (capacity) constraints as possible to make the model represents reality as much as possible. It is likely to solve the problem separately for each packaging line. The number of SKUs that are produced on the packaging lines differs from around 10 to 40. Because of the separate problems, the recipes included in each subproblem are limited. It could be that the mathematical problem is solvable with the included solver in Excel. However, it could be that we need some heuristics are necessary to obtain a near-optimal solution. In the following chapter, a literature review is conducted on lot sizing models and solution methods for those models.

3. LITERATURE REVIEW

The goal of this chapter is to get a deeper understanding of lot sizing problems by doing a literature review. Section 3.1 gives a general introduction to lot sizing techniques and provides a clear classification of the available approaches. In Section 3.2, the specific capacitated lot sizing problem is further elaborated and the extension with setup costs and setup times is discussed. Next, the complexity and the possible solution approaches are explained. In addition, we talk about the possibility of performing a sensitivity analysis to give a good conclusion about the results of a model. In Section 3.3 the production wheel, a different approach less frequently mentioned in the literature, is discussed. This chapter is finished with a conclusion in Section 3.4.

3.1 LOT SIZING MODELS

The question of when to produce a specific quantity of a product is very common in literature. However, there is still not a straightforward answer to this question due to the complexity of the problem and the many different approaches available. The decision on the production quantities should be made by finding an appropriate trade-off between the costs. This optimization problem is referred to as a *lot sizing problem* in literature and therefore this term is used in this literature review.

One of the first lot sizing problems defined in the lot sizing literature is the Economic Order Quantity (EOQ) problem by Harris (1913). The model determines the EOQ for one single item by analysing the trade-off between inventory and setup costs. When the demand rate is approximately constant, the use of the basic EOQ is advocated. Instead of assuming a continuous and infinite time period, Wagner and Whitin (1958) consider a finite time horizon that is divided into several discrete time periods, or buckets. However, this algorithm is complex and has some drawbacks and therefore, over the years, heuristics are proposed to determine the production quantities. The most common ones are Silver-Meal heuristic, Least Unit Cost, Lot-For-Lot, Part Period Balancing and the EOQ Time supply (Ramya, Rajendram, Ziegler, Mohapatra, & Ganesh, 2019). Tests in a rolling-horizon environment (see, e.g., Blackburn and Millen 1980) have revealed that frequently the Silver–Meal heuristic outperforms the dynamic programming Wagner and Within algorithm.

Instead of calculating the lot size of a single item, there are also mathematical lot sizing models to determine the lot size of multiple items. The complexity of lot sizing problems depends on the features considered by the model. It is helpful to classify the lot sizing models to indicate which model applies to this case study. The lot sizing models can be classified based on many features such as the planning horizon, number of levels, number of products, capacity of recourse constraints, deterioration of items, setup structure, and inventory shortage (Karimi et al., 2003). According to Gicquel, Minoux, & Dallery (2008), the complexity of a model is strongly affected by the planning horizon, the number of levels, and the number of resources, so these are further discussed in detail.

The *Planning horizon* is the time interval on which the master production schedule extends in the future. The planning horizon can be defined as finite or infinite. In a finite time horizon, the demand for the products may vary in every period (dynamic demand), nevertheless, in an infinite time horizon, normally a constant demand rate (stationary demand) is assumed similar to the EOQ model (Ramya, 2019). While looking at the size of the planning periods, we differentiate between small- and large-bucket models. Within large-bucket models, multiple products can be produced while in small-bucket models the period is so short, for instance one hour, that only one product can be produced.

The next important characteristic is the *number of levels*; single-level or multi-level products. In a single level system, the product can be produced by one single operation from raw material to end product. Product demands are assessed directly from customer order or demand forecast, in literature this demand is known as independent demand. In a multi-level problem, several separate operations are needed to transform the raw materials into the finished product.

The *number of resources* can be divided into either single-machine or multi-machine. The use of parallel machines complicates the problem as we not only have to determine the timing and level of production, but we also must assign production lots to machines.

Referring to our problem, we are dealing with a finite planning horizon. As explained in Chapter 2, the planning horizon for this lot sizing problem will be around six months. Furthermore, our lot sizing problem focuses only on the filling process and therefore it is a single-level system with multiple products. The plant in Aalter is a multi-machine system, as several packaging lines operate in parallel. In addition, the problem is a capacitated problem because there are restrictions on the availability of the capacity on resources. The setup structure in our problem can be termed as a complex setup because the setup times are sequence-dependent.

3.1.1 Classification of lot sizing models

A lot of variants of the lot sizing models are presented in the literature. In this section, a complete classification of lot sizing problems is explained. A schematic overview of the classification is given by Ramya et al. (2019) and is shown in Figure 12.

The lot sizing models can be classified as continuous lot sizing problems and dynamic lot sizing problems. In continuous lot sizing problems, the time scale considered is continuous and the planning horizon is infinite. The classic economic lot scheduling problem comes under the class of continuous and capacitated lot sizing problems (Salomon, 1991). This model is an extension of the EOQ model when several products are to be produced on the same machine (Karimi et al., 2003). When capacity restrictions are involved, solving the economic lot scheduling problem is NP-hard (Ramya et al., 2019).

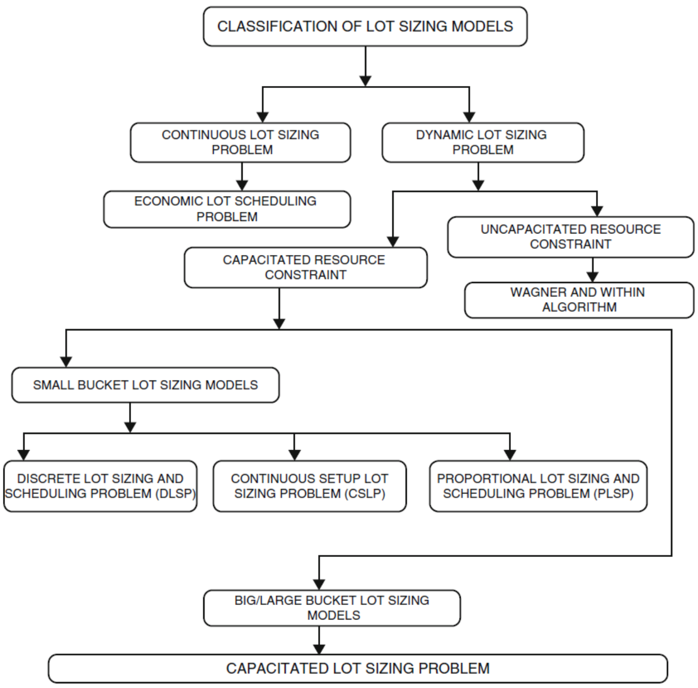

Figure 12: The classification of lot sizing problems

The dynamic lot sizing problems deal with lot sizing decisions for single/multiple items when the demand is assumed to be deterministic and time-varying. It is further classified into uncapacitated and capacitated lot sizing problems. The uncapacitated single-level lot sizing problem was addressed by the earlier mentioned Wagner and Whitin (1958), by assuming the demand to be dynamic and deterministic. The major limitations of the Wagner-Whitin approach are the amount of computer memory and the computation time required for large problems (Sajadi, Arianezhad, & Sadeghi, 2009). Since the algorithm proved to be inefficient to solve problems involving many products, several heuristics were proposed during the 1960s and 1970s.

In the book of Ramya et al. (2009) the capacitated lot sizing problems are further classified into small- and large-bucket lot sizing models, based on the length of the time period. The capacity restrictions make it very hard to solve the lot sizing problems using techniques like dynamic programming. Therefore, one or at most two setups can take place in a period. There are different types of small-bucket models introduced in lot sizing literature of which the three most common ones are: Discrete lot sizing and scheduling problem, continuous setup lot sizing problem, proportional lot sizing and scheduling problem. Because only one product can be produced in each period, these lot sizing models do take the scheduling part into account.

On the other hand, the large-bucket lot sizing model is called the capacitated lot sizing problem (CLSP). This problem is referred to as the optimal production plan for multiple items with sequence-independent setup costs, and without any setup times, having capacity constraints for a single machine. The planning horizon has a finite number of periods. The products face a dynamic and deterministic demand. If the products must be set up in a certain period, the resources have to be set up for the product in that period. The setup of a product incurs a setup cost and consumes a certain amount of capacity in that period. The main objective of the CLSP is to minimize the sum of the setup and inventory costs of all products across all time periods. There are variations of the CLSP addressed in the literature under which the CLSP with sequence-dependent setups. This hybrid model assumes sequence-dependent setup costs and setup times. The CLSP is also 'hard' in a practical sense since optimal solution methods have failed to solve all but very small problems within reasonable computation times. It is therefore not surprising that most algorithms are heuristic in nature (Salomon, 1991).

As the plant tries to schedule all production on working days (15 shifts), the production in the plant should stop at the end of the week on Friday and starts at the beginning of the next week on Monday morning. We define this situation as packaging lines that operate in a discrete setting. With the other characteristics described in the previous section, the CLSP seems to be the best fit for the problem that we are addressing in this research. The following section will focus on this lot sizing model.

3.2 Capacitated Lot Sizing Problem

The Capacitated Lot Sizing Problem (CLSP) determines the lot sizes for multiple items that face time-varying demand and are produced on a resource with limited capacity over a finite time horizon (Karimi, Ghomi, & Wilson, 2003). The objective of the problem is to minimize total costs, consisting of setup costs, production costs, and inventory costs. The accompanying mathematical formulation of the CLSP formulated by Karimi et al. (2003) is as follows:

Sets

I	set of items (i = 1, …, N)
T	set of time periods (t = 1, …, T)

Parameters

S_{it}	Setup costs when item *i* is produced in time period *t*
C_{it}	Variable unit production costs for item *i* in time period *t*
h_{it}	Unit inventory costs for item *i* at the end of period *t*
R_t	Available capacity in time period *t*
d_{it}	Demand for item *i* in time period *t*
a_i	Unit resource consumption for item *i*
$M_{it} = \sum_{k=t}^{T} d_{ik}$	Upper bound on the production of item *i* in time period *t*

Variables

X_{it}	Production of item *i* in time period *t*
I_{it}	Inventory for item *i* at the end of time period *t*
Y_{it}	A binary variable: 1 if there is production for item *i* in time period *t*; 0 otherwise

Objective function

Minimize $$Z = \sum_{i=1}^{n} \sum_{t=1}^{T} (S_{it} * Y_{it} + C_{it} * X_{it} + h_{it} * I_{it}) \quad (1)$$

Subject to

$$\sum_{i=1}^{n} a_i * X_{it} \leq R_t, \quad \forall t \in T \quad (2)$$
$$X_{it} + I_{i,t-1} - I_{it} = d_{it}, \quad \forall t \in T, \forall i \in I \quad (3)$$
$$X_{it} \leq M_{it} * Y_{it}, \quad \forall t \in T, \forall i \in I \quad (4)$$
$$X_{it} \geq 0, I_{it} \geq 0, Y_{it} \in \{0,1\} \quad \forall t \in T, \forall i \in I \quad (5)$$

The objective is to minimize the total costs by determining the production quantity of all items and planning horizon *T*. Constraints (2) ensures that the capacity on the packaging line in period *t* is equal to or smaller than the maximum capacity assigned to that packaging line in each period. The inventory balance constraints (3) ensures that all demand is satisfied regarding requirements. Constraint (4) makes sure that an item can only be produced when a setup is assigned in that specific period. In addition, the production quantity in each time period is restricted to be smaller than the total demand for that item from the period under consideration until the last period. Constraint (5) are basic constraints that ensure that the variables are positive values or binary respectively.

By adding sets, constraints, or variables to the above mentioned CLSP, we can model our situations. One important aspect is to extend the CLSP by including setup times and costs. In Chapter 4 the mathematical model for this research is explained in detail. First, we discuss the various options for including the setup costs and setup times in a CLSP, as found in literature in the next sections.

3.2.1 The complexity of the problem

The CLSP is a mathematical problem in the category of the Mixed Integer Linear Programming (MILP). This is because the setup variable is required to be a binary variable; there is a setup (the value of the variable is equal to one), or not (the value of the variable is equal to zero). Unfortunately, a MILP is much harder to solve than a 'simple' Linear Problem (LP). In fact, at present, no approach or algorithm can solve instances of these problems in an efficient way (Winston, 2004). Florian et al. (1980) and

Bitran and Yanasse (1982) proved that the single-item CLSP is NP-hard. NP-hard problems are problems for which the optimal solution most likely cannot be found within polynomial time (Schuur, 2007).

At the plant in Aalter, we face a problem that is an extension of the single-item CLSP. This implies that the problem that we face is NP-hard as well. By including setup times, we increase the complexity of the problem. There is little research available that focuses on developing solutions for the CLSP problem with sequence-dependent setup costs and setup times. Nevertheless, more researchers developed solutions for the CLSP that is extended with sequence-dependent setup costs only.

3.2.2 CLSP with sequence-dependent setup costs and setup times

The capacitated lot sizing problem is known as the large-bucket approach. In the above-discussed CLSP, detailed scheduling decisions are not integrated (Gicquel et al., 2008), meaning that the CLSP solves the lot sizing problem, but not the scheduling problem. A variant to this problem is the CLSP with sequence-dependent setup costs and non-zero setup times. Considering set up costs when they are sequence-dependent implies that plant managers must decide which products to make in which periods, and the exact production sequence and production quantities to minimize the sum of different costs. Thus, they must tackle both a lot-sizing and a scheduling problem (Memmi & Laaroussi, 2013). The CLSP with sequent-dependent setup costs is related to the travelling salesman problem (TSP). The distance (or cost) matrix in the TSP is equivalent to solving multiple dependent TSP's. Like the TSP, the CLSP also belongs to a set of problems that are called NP-hard. What makes this problem particularly difficult to solve in many applications is the fact that capacity is tight, setup costs are large and sequence-dependent, and setup times are non-zero (Gupta & Magnusson, 2005).

A few studies have been done on the CLSP with sequence-independent and in all articles, the authors obtain a heuristic solution. Meyr (2000) models and solves the problem of integrating lot sizing and scheduling of several products on a single, capacitated production, taking into account sequence-dependent setup times. He determines and schedules continuous lot sizes that meet deterministic dynamic demands and minimize inventory costs and sequence-dependent setup costs. He develops a general algorithmic approach where a dual re-optimization algorithm is combined with a local search heuristic. He proves with computational tests the effectiveness of his solution method.

Gupta and Magnusson (2005) study a single machine capacitated lot sizing and scheduling problem with sequence-dependent setup costs and non-zero setup times. They provide an exact solution restudied by Almada-Lobo, Oliveira, & Carravilla (2008), and a heuristic to solve large problem instances. The authors state that their heuristic is more effective when there are many more products than there are planning periods. Due to the complexity, the heuristics proposed should not be expected to completely substitute a human expert in the production planning process stated Gupta et al. (2005). Rather, it can be viewed as a tool that can generate an initial solution and provide valuable guidance to managers of manufacturing facilities.

3.2.3 Solution methods for CLSP with sequence-dependent setup times

As we mentioned, little research focuses on developing solutions for the CLSP with setup costs and setup times. Gupta and Magnusson (2005) claim that, before they carried out their research, there exists no literature in which a solution for the CLSP containing sequence-dependent setup times is developed. Also, they indicate that only a few papers discuss solutions for the CLSP that contains sequence-dependent setup times, while these papers only present approximate solutions for the problem. Gupta and Magnusson (2005) developed a heuristic suitable for a production environment that operates in a continuous setting. Their heuristic searches for a feasible solution by considering the problem period-by-period, as well as item-by-item:

1. A planning for one product family individual is constructed, by considering the complete horizon period-by-period.
2. Add another product family to the planning, such that the product family that is introduced first used the complete capacity of the resource. The product family that is introduced second can only use the remaining production capacity. When the capacity is violated, the excess production is moved to the next period. When capacity violations occur, excess production is shifted to the preceding period.
3. Due to the backwards approach, only week one can have a capacity violation. Therefore, product families are moved to succeeding periods to reduce the capacity in week one.

Gupta and Magnusson (2005) solve this MILP via optimization software and assess their results. The average deviation between the heuristic and the exact solution ranges between 10% and 16%. However, they only tested their MILP for four small problem instances. The problem contains 6, 8, 7, or 11 items in respectively 5, 4, 3, and 2 time periods. The computation time will increase exponentially when the number of items and/or periods is increased. These results of the CLSP with setup times are not satisfying. But on the other sides, methods such as branch-and-bound, Lagrangean relaxation, or LP-based techniques are difficult to implement in Microsoft Excel and difficult to maintain and execute by personnel.

In contrast, Ozdamar and Bozyel (2000) consider the CLSP with sequence-independent setup times and costs as well. They developed a Simulated Annealing (SA) algorithm and tested their problem for several problem instances; 4, 10, and 15 items in 6 and 10 time periods. Their model shows promising test results and they state that their model outperforms other approaches. In addition, Salomon (1991) also indicate that SA has the advantage of being easy to understand, implement, and can attain (reasonable) solutions to complex problems. SA is an iterative approach that makes use of a Neighbourhood Solution (NS). A disadvantage of SA, according to Salomon (1991), is that the quality is hard to predict and that SA has an experimental character. In addition, Tang (2004) indicates that the quality of the SA algorithm depends on how the NSs are defined and that SA can be slow. As such, Tang (2004) proposes combining SA with a fast heuristic.

3.2.4 Solution methods for CLSP with sequence-dependent setup costs

Other research is done that focuses on developing heuristics for the CLSP that is extended with sequence-dependent changeover costs only. Maes and Van Wassenhove (1988) have written an extensive review on this topic. They assess the results of several heuristics in combination with different problem instances. They conclude that the heuristics based on a branch-and-bound algorithm, the LP-based heuristics, and Lagrangean relaxation can give good results. However, these heuristics often have a high computation time.

They also assessed the simple and fast heuristics of Lambrecht and Vanderveke (1979), Dixon and Silver (1981), Maes and Van Wassenhove (1986), and Dogramaci et al. (1981) for the same problem instances. We refer to these heuristics as the LV, DS, MW, and DPA heuristic respectively. All these heuristics are based on the period-by-period heuristics and can be easily implemented on a personal computer. The overall conclusion of Maes and Van Wassenhove is that the LV, DS and MW heuristics perform well on average, but there can be large deviations for specific problem instances. More researchers agree on the good results of the DS heuristic. Graves (1981) indicates that the DS heuristic seems to be the most effective heuristic for the CLSP with changeover costs. According to Bahl et al (1986), the DS heuristic scores well on most of the classification criteria they present in their research, in contrast to most other heuristics.

The DS heuristic generates an initial planning based on the lot-for-lot rule. Next, the remaining capacity per week is determined and the quantity to produce to stock to generate a feasible planning is calculated. This process starts in the first week until the last week on the horizon. If in a certain period the production capacity is violated, (a part of) a production run is shifted to a preceding period. When shifting these production runs, the heuristic verifies what reallocation results in the most positive, or least negative, impact on the total costs per unit of time and unit of capacity. The average Costs unit of time for item *i* when considering one run that covers T_i periods of demand is given as follows:

$$AC_i(T_i) = \left(S_i + h_i \sum_{j=1}^{T_i} (j-1) d_{ij}\right) / T_i$$

Where T_i represents the number of periods of demand that a run of item *i* satisfies. The DS heuristic reallocates the item with the largest possible u_i, which is given by:

$$u_i = (AC_i(T_i) - AC_i(T_i + 1)) / (k_i * d_{i,T_{i+1}})$$

Where k_i represents the resource requirement for item *i.* If u_i is the marginal decrease in the average cost per unit of absorbed capacity, then the heuristic should increase the time supply of the item with the largest positive u_i. When no time period violates the production capacity, production runs are combined to improve the planning. Runs are combined when the combination results in a reduction of the total costs based on the u_i values. The DS heuristic is an extension of the Silver-Meal heuristic. In the Silver-Meal heuristic, the AC_i would be optimized for every item but no capacity constraints are considered. The DS heuristic considers the CLSP, while the Silver-Meal heuristic considers the uncapacitated lot sizing problem.

3.3 PRODUCTION WHEEL

In the literature, a totally different process is proposed according to determining production quantities and a production schedule. The product wheel is a heuristic method for gaining economies of repetition while simultaneously responding to needs for increased variety and flexibility towards the end customer. A product wheel, like a schedule block, is a method for natural sequencing which uses a flexible scheduling sequence for production that is based on demand, changeover times, production rates, and inventory carrying costs (King & King, 2013).

A product wheel is a visual metaphor for a structured, regularly repeating sequence of the production of all the materials to be made on a specific product on a packaging line. The overall cycle time for the wheel is fixed. The time allocated to each product (a "spoke" on the wheel) is relatively fixed, based on that product's average demand over the wheel cycle. The sequence of products is fixed, having been determined from an analysis of the path through all products that will result in the lowest total changeover time or the lowest overall changeover cost. The method includes 10 steps that assess various aspects of the production system and scheduling practices.

1. Decide which assets would benefit from product wheels.
2. Analyse product demand variability.
3. Determine the optimum production sequence.
4. Calculate the shortest wheel time based on time available for changeovers.
5. Estimate the economic optimum wheel time based on Economic Lot Size (ELS) model.
6. Determine the basic wheel time and determine which products are made on every cycle and the frequency for other products.
7. Calculate inventory levels to support the wheel.
8. Repeat Steps 3-7 to fine-tune the design.
9. Revise all scheduling processes, as appropriate.
10. Create a visual display (heijunka) to manage the levelled production.

It is important that the stock levels and corresponding lot sizes are adjusted for the changing market needs and demand seasonality while making the product wheels in a real production scheduling scenario. However, the sequence of the production runs should remain the same since it is designed to reduce the total changeover time and inventory costs based on natural sequencing. Trattner, Herbert-Hansen and Hvam (2018) applied the product wheel heuristic approach and tested the production cycles generated using actual sales and production data from a manufacturer of frozen baked goods. The product wheel method showed to be a suitable method for application at the baked goods manufacturer and generated a 23% reduction in setup and inventory cost at the case company.

Despite the benefits, the product wheel method proved difficult to apply in a high variety setting. The presence of sequence-dependent changeover times made the manual task of step 3 quite tricky. Moreover, step 4 was not readily applicable given their 81 times taken into account. Trattner et al. (2018) state that the product wheel method is not the best fit for production scenarios in the process industry which have a high number of make to stock products. In a study on product wheels at a chemical manufacturer, only eight products were included in the product wheel design, so this was much simpler to generate the schedule for (Wilson & Ali, 2014). This suggests that the product wheel is more suitable for smaller scheduling problems and high variety settings an operations research model may achieve more significant results.

3.4 Conclusion

In this chapter, we carried out a literature review to answer our second sub-question: *"Which methods found in the literature regarding the optimization of the tactical production planning are suitable for this research?".* This literature review shows that determining lot sizes including sequence-dependent setup cost and setup times is challenging and requires difficult mathematical models. The models currently developed are operations research models, heuristics and lean scheduling methods, such as the product wheel. These models and tools are often customised to incorporate specific constraints, such as the perishability of the products and sequence-dependent setup costs and times.

In this research, we face a problem which is a multi-item problem with dynamic demand. There are a few capacity constraints that must be included in the model and there are multiple items produced during one time period, which indicates a large-bucket situation. So, we can conclude that the problem that we face fits best with the capacitated lot sizing problem (CLSP). These models are often not solvable towards optimality and heuristics are more suitable to obtain a feasible solution.

After consulting with the stakeholders of our research, we decided to address this problem with a Mixed Integer Linear Programming (MILP) model. This will be an extension of the problem described in Section 3.2. This choice is made because FrieslandCampina prefers a model that uses little to no programming language, so that is quick and easy to learn and use. Preference was also given to a program that is known and used by many of their colleagues instead of introducing a new programming language. Although the instances of the problem are quite large and we have discussed the different options in detail with the stakeholder, we have decided to solve the MILP in Microsoft Excel towards optimality. It is doubtful whether this is feasible according to our literature review, so we create a pilot version of the model first. Based on the results of this pilot, we decide to continue with the MILP or to switch to a heuristic approach.

In the next chapter, we present a MILP that represents the lot sizing problem of FrieslandCampina.

4. MATHEMATICAL MODEL DESCRIPTION

In this chapter, we develop our mathematical model. First, we describe the problem that we encounter in words, which results in the conceptual model in Section 4.1. Next, we develop our mixed linear integer programming model in Section 4.2 with the indices, parameters, objective function, and all constraints. In Section 4.3 we briefly discuss some adjustments that need to be carried out manually. Lastly, we describe different models in Section 4.4, that we develop to do different tests with our mathematical model. We close this chapter with a conclusion in Section 4.5.

4.1 CONCEPTUAL MODEL

Before we dive into the mathematical model, we first describe the problem in words. The production department consists of 17 packaging lines, that each can produce a specific set of SKUs. Some of these packaging lines are connected to the same aseptic tank, which means that those packaging lines cannot fill different recipes at the same time. Therefore, some of those packaging lines are combined as one packaging line with double capacity. In the model, we focus on 14 (combined) packaging lines. There are 301 SKUs and each SKU is assigned to its own packaging lines. So, if there is any production scheduled for an SKU, it is known at which packaging line this is done.

In the model, we aim to minimize the total costs incurred for the chosen drumbeat patterns. The drumbeat patterns are chosen at the product family level. A product family can consist of multiple SKUs with the same and/or different recipes. The products are part of the same product family for various reasons. First, if the SKUs are produced on the same packaging line and have the same recipe, they belong to the same product family. If there are a lot of SKUs with the same recipe, we look at the forecast and make two product family groups and place the SKUs with similar forecast quantities in the same product family. Second, if SKUs have a different recipe but no CIP is needed between these recipes, we place them in the same product family. Third, if there are specifications that require SKUs to be produced together or must follow the same drumbeat pattern, we put the SKUs in the same product family. We established and validated these 94 groups together with the Supply Network Planners of FrieslandCampina. In Figure 13 we show the hierarchy between the SKUs, the recipe and the product family. So, one product family could exist of multiple recipes and the recipes can have multiple products. This is not always the case; a product family can also exist of one recipe with one SKU at one packaging line. A product family can consist of SKUs of multiple packaging lines.

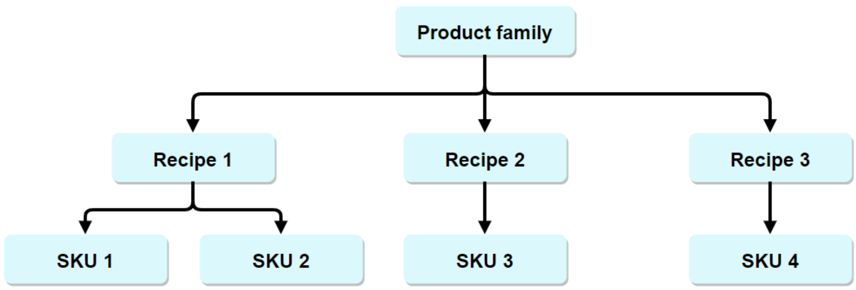

Figure 13: Hierarchy of the subsets

The product family, recipe and product variables are all binary variables. If the value for a product family at a packaging line in a particular week is 1, all products in that product family can be produced. However, this is not necessary as long as the minimum production quantities at the recipe level are met. Therefore, we need the binary variable at the recipe level. We add up the quantities of one recipe across all packaging lines to verify that the minimum production quantity is met in that week. On the other hand, we use the variable at the recipe level to control if a recipe is produced on a single packaging line to take into account the setup costs and time. The binary variable at the product level is then used to assign a production quantity to an SKU on a packaging line in a given week and to manage the inventory costs across all weeks. When the value of a product family at a packaging line in a week is zero, no production is allowed for any SKU in that product family, no minimum production quantity has to be met and no setup costs and times are incurred.

As mentioned, the objective is to minimize the total costs for these chosen drumbeat patterns at the product family level. Costs minimization is accepted only when all forecasted demand is met. So, no backorders are allowed. We consider setup and inventory costs. The setup costs depend on the sequence of the SKUs, as switching from one SKU to another can require the packaging line to be cleaned, sterilised and/or changed. The costs differ per option and can vary from packaging line to packaging line. We consider three types of setup costs and setup times. First, the setup costs that arise at the level of the product family. When SKUs from a product family are produced at a packaging line, we assume that a CIP is required, and the associated costs and time are taken into account. This will almost always be valid because all recipes which can be produced without a CIP are combined. Second, we look at the setup costs and setup times at the recipe level. This includes changing a packaging line from one packaging to another and/or simply cleaning the packaging line with water. This option is less expensive and less time consuming than the product family setup. Third, we consider a setup if a format change is needed. There are only five packaging lines that can fill packages in multiple sizes. In most cases, this results in high changeover time and high costs. For these five packaging lines, we need an extra subset to determine which format is produced in which week. If two or more SKUs with different sizes are produced at a packaging line in a given week, we charge the cost and time for a format changeover. Because all SKUs are assigned to their own packaging line, we know exactly which format will be produced each week.

On the other hand, we have the inventory costs per SKU per week. These costs are charged at the product level. Because we know the exact amount of production and the forecasted demand per SKU per week, we can calculate the stock levels and take into account the associated costs at the product level. In addition, we consider the cost incurred because money is tied up in inventory, rather than being used for investments or debts. This is included in the inventory costs per SKU. The inventory costs are charged at the end of each week. In addition, the inventory level must always meet the safety stock level.

The demand is forecasted, and no backorders are allowed. In the model, we do not look at the first 12 weeks of the forecast. These weeks are within the scope of the supply network planners and they can adjust these production quantities manually based on sales orders. The model is used on a tactical level and will be run twice a year. Therefore, we skip the first 12 weeks and look 24 weeks ahead from week 13. To make it possible in the model to choose a drumbeat of *0001*, we need to make sure that the initial inventory is high enough to cover the first three weeks without production. To do this, we equate the initial inventory to the sum of the forecast of the first four weeks plus the safety stock at week 16, the fourth week in the model. So, the initial inventory is exactly enough for the first four weeks without any production.

The capacity of the packaging line depends on the number of shifts that are scheduled. Besides, the manning capacity restriction, the quantities that are produced are limited by the minimum and maximum production quantities at the recipe level. These minimum and maximum production quantities are restrictions of the mixing process which happens before the packaging department.

4.1.1 Constraints & assumptions

As described in Chapter 2, there are many constraints in the complex plant in Aalter that can be considered. Due to the complexity and the focus on the tactical planning, constraints at the SKU level are not taken into account. Whether an SKU should be produced every two weeks due to agreements with the customer or whether an SKU is preferred to be in a different week than another SKU, are not included. The constraints that are included to ensure a feasible solution are as follows:

- All demand is fulfilled on time and before the end of the planning horizon.
- The capacity of a packaging line cannot be violated.
- The inventory level of each product must meet the safety stock level.
- If a recipe in a certain week is produced, the quantity is constrained by a minimum and a maximum production quantity.

To be able to solve the problem we made several assumptions as well:

- Production is always performed without errors.
- Setup times between weeks is not considered; the packaging line is always prepared again at the start of each week.
- There is no limit to the inventory capacity.
- Enough raw materials are in stock and enough milk is delivered to produce the products.

4.2 Mathematical model

Based on the CLSP model described in Section 3.2 and the conceptual model in Section 4.1, we create a MILP for determining the drumbeat patterns for all SKUs. This model calculated the best drumbeat pattern for each SKU, which indicates the production moments. Bases on these drumbeat patterns, we can calculate the production quantity and inventory levels directly.

4.2.1 Sets & indices

We created several indices to refer to different elements in an array. The first array refers to all products that are produced in the plant. Next, we make three subsets of all these products. The first subset can consist of multiple items which are part of the same product family. The second subset combines all items that are made from the same recipe. The other subset consists of items with the same format on a packaging line. Also, the time periods, the drumbeat patterns and the different packaging lines are specified.

I	$Set\ of\ product\ i$ $(\mathrm{i} = 1, \dots, \mathrm{I})$
I_f	$Set\ of\ products\ i\ in\ product\ family\ f$ $(\mathrm{f} = 1, \dots, \mathrm{F})$
I_r	$Set\ of\ product\ i\ made\ by\ recipe\ r$ $(\mathrm{r} = 1, \dots, \mathrm{R})$
I_u	$Set\ of\ product\ i\ with\ format\ u$ $(\mathrm{u} = 1, \dots, \mathrm{U})$
T	$Set\ of\ time\ periods\ t$ $(\mathrm{t} = 1, \dots, \mathrm{T})$
N	$Set\ of\ drumbeats\ patterns\ n$ $(\mathrm{n} = 1, \dots, \mathrm{N})$
K	$Set\ of\ packaging\ lines\ k$ $(\mathrm{k} = 1, \dots, \mathrm{K})$

4.2.2 Parameters

Here we list the parameters that serve as input for the model. All this information is known in advance and stored in the model.

d_{it}	$Forecast\ for\ product\ i\ in\ time\ period\ t$
c_{tk}	$Available\ capacity\ in\ time\ period\ t\ at\ line\ k$
a_{it}	$Safety\ stock\ required\ for\ product\ i\ in\ time\ period\ t$
p_{ik}	$Unit\ resource\ consumption\ for\ product\ i\ on\ packaging\ line\ k$
v_i	$Format\ in\ liters\ of\ product\ i$
MOQ_r	$Minimal\ production\ quantity\ for\ recipe\ r$
MAX_r	$Maximum\ production\ quantity\ for\ recipe\ r$
h_{it}	$Unit\ inventory\ costs\ for\ product\ i\ at\ the\ end\ of\ period\ t$
s_{ftk}	$Setup\ costs\ incurred\ if\ product\ family\ f\ is\ produced\ in\ time\ period\ t\ at\ line\ k$
t_{ftk}	$Setup\ time\ inccured\ if\ product\ family\ f\ is\ produced\ in\ time\ period\ t\ at\ line\ k$
s_{rtk}	$Setup\ costs\ incurred\ if\ recipe\ r\ is\ produced\ in\ time\ period\ t\ at\ line\ k$
t_{rtk}	$Setup\ time\ inccured\ if\ recipe\ r\ is\ produced\ in\ time\ period\ t\ at\ line\ k$
s_{utk}	$Setup\ costs\ incurred\ if\ format\ changeover\ u\ is\ required\ in\ time\ period\ t\ at\ line\ k$
t_{utk}	$Setup\ time\ inccured\ if\ format\ changeover\ u\ is\ required\ in\ time\ period\ t\ at\ line\ k$
M	$A\ Large\ number$

$$b_{nt} = \begin{cases} 1, if\ drumbeat\ n\ allows\ production\ in\ time\ period\ t \\ 0, otherwise \end{cases}$$

$$I_{io} = \sum_{k=1}^{4} d_{ik} + a_{i4} \qquad Starting\ inventory\ for\ product\ i\ in\ the\ first\ time\ period$$

4.2.3 Decision variables & auxiliary decision variables

We also need decision variables, which constitute the output of the model. Our main decision variable is the drumbeat pattern that is chosen for each product family. Based on the value of this decision variable the production quantity, the inventory levels, the setups and all costs aspects can be calculated. This decision variable is indicated as follows:

$$Q_{fn} = \begin{cases} 1, if\ for\ product\ family\ f\ drumbeat\ pattern\ n\ is\ chosen \\ 0, otherwise \end{cases}$$

The other variables are auxiliary decision variables, which are used to translate the constraints as described in Section 4.1.1 into mathematical formulations. They do not represent an action that a product would follow but they are still outputs of the model as their value is based on that of Q_{fn}. For example, if a drumbeat pattern is chosen for product family *f*, we know in which week the products *i* in that product family can be produced. Subsequently, we know for each week if a setup is needed, what production quantities will be produced, which recipes will be produced at a packaging line, which recipes are produced each week, which formats are filled and how much inventory is left at the end of a week.

X_{it}	$Production\ quantity\ of\ product\ i\ in\ time\ period\ t$
I_{it}	$Inventory\ for\ product\ i\ at\ the\ end\ of\ time\ period\ t$

$$Z_{ftk} = \begin{cases} 1, if\ there\ is\ production\ for\ product\ family\ f\ in\ time\ period\ t\ at\ line\ k \\ 0, otherwise \end{cases}$$

$$W_{rtk} = \begin{cases} 1, if\ there\ is\ production\ for\ recipe\ r\ in\ time\ period\ t\ at\ line\ k \\ 0, otherwise \end{cases}$$

$$G_{rt} = \begin{cases} 1, if\ there\ is\ production\ for\ recipe\ r\ in\ time\ period\ t \\ 0, otherwise \end{cases}$$

$$J_{utk} = \begin{cases} 1, if\ a\ format\ changeover\ is\ required\ to\ format\ u\ in\ time\ period\ t\ at\ line\ k \\ 0, otherwise \end{cases}$$

4.2.4 Objective function

The objective function is a minimization of the setup and the inventory costs over all products *i* and all time periods t in the planning horizon. The objective function consists of four parts, which we describe in more detail. The first part sums over all product families, all time periods, and all packaging lines to calculate the total setup costs over all product families. The setup costs per product family are multiplied with the binary variable if a product family is produced in that time period. This component indirectly minimizes the number of setups, as costs are assigned to each setup. The second part of the objective function calculates the total setup costs over all recipes. The third part calculates the total setup costs for changing the format over all packaging lines. These two parts are similar to the setup costs of the product families but now focused on the recipe and format level. The last part calculates the inventory costs by multiplying the end of week inventory with the inventory costs, in which the capital costs are also included. This component ensures the inventory levels are minimized on average.

$$\text{Minimize} \quad Z = \sum_{f=1}^{F}\sum_{t=1}^{T}\sum_{k=1}^{K}(s_{ftk} * Z_{ftk}) + \sum_{r=1}^{R}\sum_{t=1}^{T}\sum_{k=1}^{K}(s_{rtk} * W_{rtk}) + \sum_{u=1}^{U}\sum_{t=1}^{T}\sum_{k=1}^{K}(s_{utk} * J_{utk}) + \sum_{i=1}^{I}\sum_{t=1}^{T}(h_{it} * I_{it}) \quad (1)$$

4.2.5 Constraints

Multiple constraints are needed to make sure that the model represents reality as much as possible. In this section, we explain the different constraints and give the mathematical notion.

Constraint (2) ensures that in each week the total production time for all items plus the total setup time for each product family, recipe, and format changeover does not violate the maximum capacity per packaging line. If a product family is produced in a week, this results in a setup for this product family. The same holds for the recipes if they are produced in that week and the format changeovers if they are required. We assume that it is required to change the format and to carry out a CIP at the beginning of the week. Therefore, no standard setup is included at the beginning of the week. It could be that no setup is needed due to the ending state of the previous week, but this will only lower the total costs even more. By this assumption, we limit the size of our problem.

$$\sum_{i=1}^{I} p_{ik} * X_{it} + \sum_{f=1}^{F} Z_{ftk} * t_{ftk} + \sum_{r=1}^{R} W_{rtk} * t_{rtk} + \sum_{u=1}^{U} J_{utk} * t_{utk} \leq c_{tk}, \quad \forall t \in T, \forall k \in K \quad (2)$$

In constraint (3) we state the balance equation for the demand. The demand must be met from inventory from the previous time period or production in the current time period. The initial inventory is provided by the forecast for the first four weeks plus the safety stock for week four. This is done to give the model the option to choose a drumbeat pattern with only one production moment in week four. Excess inventory is carried over to the next time period. Next, the inventory should be equal to or larger than the safety stock of that product. In constraint (4), we give this mathematical constraint.

$$X_{it} + I_{i,t-1} - I_{it} = d_{it}, \qquad \forall i \in I, \forall t \in T \qquad (3)$$

$$I_{it} \geq a_{it}, \qquad \forall i \in I, \forall t \in T \qquad (4)$$

Each product family needs its own drumbeat pattern. Constraint (5) makes sure that each product family can only choose one of those drumbeat patterns.

$$\sum_{n=1}^{N} Q_{fn} = 1, \qquad \forall f \in F \qquad (5)$$

Five additional constraints are required to ensure that the auxiliary variables have the correct values. With the drumbeat pattern chosen for each product family, we can derive the production pattern for the auxiliary variable Z_{ftk} in constraint (6) for product families in all time periods. In constraints (7) we make use of the big M method to derive the auxiliary variable W_{rtk}. This constraint ensures that if one or more items of a certain recipe are produced in a certain week, the auxiliary variable W_{rtk} will become one. If no item of a certain recipe in a certain week is produced the variable will remain zero. The same construction is made in constraint (8) and (9) for the auxiliary variables G_{rt} and J_{uyk}.

$$Z_{ftk} = \sum_{n=1}^{N} (Q_{fn} * b_{nt}), \qquad \forall f \in F, \forall t \in T, \forall k \in K \qquad (6)$$
$$\sum_{i=1}^{I_r} X_{it} \leq M * W_{rtk}, \qquad \forall r \in R, \forall t \in T, \forall k \in K \qquad (7)$$
$$\sum_{k=1}^{K} W_{rtk} \leq M * G_{rt}, \qquad \forall r \in R, \forall t \in T \qquad (8)$$
$$\sum_{i=1}^{i \in I_u} X_{it} \leq M * J_{utk} \qquad \forall u \in U, \forall t \in T, \forall k \in K \qquad (9)$$

With the values of all the decision and auxiliary variables, we can construct the remaining constraints. Constraint (10) makes sure that the production quantity of a product is smaller than or equal to the big M multiplied with the auxiliary variable Z_{ftk}. We make use of the subset I_f, so for a product *i* we make sure that a production quantity in a week can only be allocated if production is allowed for the product family *f* to which product *i* belongs.

$$X_{it} \leq M * Z_{ftk}, \qquad i \in I_f, \forall t \in T, \forall f \in F, \forall k \in k \quad (10)$$

Next, the minimum and maximum production quantities per recipe cannot be violated. For these constraints, we need the auxiliary variable G_{rt} because we want to know if a recipe is produced in a certain week regardless of which packaging line it was produced on. Constraint (11) ensures that all products with the same recipe together produce the minimum amount in litres in a week if that recipe is produced in that week. The opposite holds for constraint (12); the sum of the quantity of all products with the same recipe cannot exceed the maximum production quantity if that recipe is produced.

$$\sum_{i=1}^{i \in I_r} (X_{it} * v_i) \geq MOQ_r * G_{rt}, \qquad \forall r \in R, \forall t \in T \qquad (11)$$
$$\sum_{i=1}^{i \in I_r} (X_{it} * v_i) \leq MAX_r * G_{rt}, \qquad \forall r \in R, \forall t \in T \qquad (12)$$

Finally, in constraint (13), (14), (15), (16), (17), (18) and (19) we state the non-negativity and binary restrictions on the decision and auxiliary variables to complete the model. The production quantity X_{it} must be integer values because no products are partially filled. The inventory level I_{it} must also be integer values but constraint (3) will force the inventory level to be an integer. Therefore, it is not necessary to include the inventory level I_{it} as an integer in the model. As mentioned above, Z_{ftk} is a binary variable. However, due to constraint (6), we know for sure that this variable can only take the value zero or one. Therefore, we can consider this variable as reals in our model. The other four variables must be considered as binary variables to ensure that only one drumbeat pattern can be chosen, and costs and production times are properly considered.

$X_{it} \geq 0;\ X_{it}\ integer \quad \forall i \in I, \forall t \in T \quad (13)$

$I_{it} \geq 0 \quad \forall i \in I, \forall t \in T \quad (14)$

$Z_{ftk} \geq 0 \quad \forall f \in F, \forall t \in T, \forall k \in K \quad (15)$

$Q_{fn} \in \{0,1\} \quad \forall f \in F, \forall n \in N \quad (16)$

$W_{rtk} \in \{0,1\} \quad \forall r \in R, \forall t \in T, \forall k \in K \quad (17)$

$G_{rt} \in \{0,1\} \quad \forall r \in R, \forall t \in T \quad (18)$

$J_{utk} \in \{0,1\} \quad \forall u \in U, \forall t \in T, \forall k \in K \quad (19)$

The full model can be found in Appendix A; model 1.

4.3 Manual adjustments

The process in the plant in Aalter is highly complicated. To align the model with reality as closely as possible we must make some manual adjustment in the model. In this section, we describe these manual adjustments and explain why they are necessary.

As explained in Section 4.1, we compiled the product families together with the Supply Network Planners. However, there are some other specifications that we must incorporate into the model. According to FrieslandCampina, there are products of which the minimum production quantity cannot be met with a drumbeat pattern of at most one production in four weeks. These products must be combined with products on different packaging lines that have the same recipe. The drumbeat pattern of some products depends on the drumbeat pattern that is chosen for their 'big brother'. Some products must be within the drumbeat pattern of another product based on sales or production decisions. This level of detail is manually included in the model in this research. The table below shows these dependencies.

Table 8: Dependencies between packaging lines

Packaging line	**Dependent of packaging line**	**Number of dependent products**
V	-	-
U	-	-
T	-	-
R	-	-
A	I+J	1
C	-	-
E+F	G+H	1
G+H	U	2
	I+H	13
I+H	-	-
K	L	1
L	C	1
X	C	4
	L	4
Y	C	1
	L	3
Z	C	5
	L	12

In this table, we see, for example, that packaging line *'G+H'* has in total 15 products that follow the drumbeat pattern of products that are filled at two other packaging lines; packaging line *'U'* and *'I+H'*. The drumbeat pattern for these 15 products are no longer a decision variable but are equal to the corresponding products on the other packaging lines. This linking process is done manually for all these 48 products.

4.4 EXPERIMENTING THE MODEL

In the MILP above, we consider multiple decision and auxiliary variables, resulting in a large decision space. With 301 products and 24 weeks in the time horizon, we have 7.224 variables for the production quantity alone. Therefore, we expect that the running time of the model will be very long. To overcome this problem and to make the model usable for FrieslandCampina we can reduce the number of variables by excluding packaging lines of the main model and examine the impact on the objective function if we solve the model for packaging lines separately. To do this analysis we introduce three different scenarios to which we adjust the model:

- All packaging lines included in one model.
- Divide the packaging lines into groups and solve the model for the groups separately.
- Design a model for all packaging lines separately.

By reducing the number of packaging lines in the different models we expect that we will achieve (near) optimal solutions in less time than the main model with all packaging lines included. In the following subsections, we describe the different options in more detail in terms of differences to our main MILP. The results of these experiments can be found in Chapter 5.

4.4.1 All packaging lines together in one model

The MILP as described in Section 4.2, is focused on the situation in which all packaging lines are included. So, for this option, we do not have to make any adjustments to the mathematical model. We expect that the running time of this model is respectively long and therefore not usable. However, it can be interesting to compare these results with the results of the other two options. What is the difference between de chosen drumbeat patterns and what is the impact on the objective function? The table below shows the specifications of this model with all packaging lines included. The model number refers to the model described in Appendix A.

Table 9: Specifications of the model with all packaging lines together

Lines included	**# SKUs**	**# Variables**	**# Constraints**	**Model Nr.**
All packaging lines	301	12,903	203,464	1

4.4.2 Packaging lines dived into groups

The second option is to split the main model into different subgroups. In Section 4.3, we already discussed the manual adjustments that we need to make due to the dependent products across packaging lines. These dependencies are shown in Table 8 and based on these dependencies we can create the subgroups. The first group consists of eight packaging lines in total of which 3 pairs have the same aseptic tank. Packaging line *'G+H'* produces products that must follow the same drumbeat patterns as comparable products on packaging line *'U'* and at packaging line *'I+J'*. That is why we combine these three packaging lines in one group. Subsequently, some products on the packaging line

'E+F' must follow the drumbeat pattern of comparable products on the packaging line '*I+J*'. For that reason, we also add the packaging line *'E+F'* to this group. The same applies to packaging line *'A'*. The first group thus consists of the packaging lines *'U, A, E+F, G+H, I+J'.* If we look at the other dependencies, we can create a second group consisting of the packaging lines *'C, L, K, X, Y, Z'.* The three remaining packaging lines do not have any dependencies with other packaging lines, but they do have some of the same recipes. Therefore, we merged these three packaging lines into the third group.

We need to make some minor adjustment to run the model for group one because the included packaging lines can all only fill one format. We can remove all parts that refer to the format changes on the packaging line. The indices, setup cost and setup time are not necessary to consider for the first group because all packaging lines in this group can only fill one format. We also can exclude the costs for the format change of the objective function. Furthermore, we can exclude the time for the format change in the capacity constraint (2) as well. Next, we can remove constraint (11) and (12) because we do not have to know if a format change is needed. The full mathematical description of the model for group one can be found in the appendix; model 2. Group two and group three follow the same mathematical model as described above with all packaging lines included. In Table 10 we show the specifications of the models per group.

Table 10: Specifications of the models of the different groups

Group	**Lines included**	**# SKUs**	**# Variables**	**# Constraints**	**Model Nr.**
1	U, A, E+F, G+H, I+J	116	5,043	45,560	2
2	C, L, K, X, Y, Z	116	4,935	38,672	1
3	V, T, R	69	2,757	18,624	1

4.4.3 All packaging lines separately in a model

To reduce the running time of the model drastically, we can tackle each packaging line separately. In this way, it is likely to find an optimal solution for each packaging line, but the model does not represent reality as close as the other options. However, it is interesting to see these differences and the optimal solution for each can give FrieslandCampina a good insight as well.

To run the model for each packaging line separately, we must make multiple adjustments to the main model. First, we can remove the index *K*, because we distinguish no longer between the packaging lines. In all parameters, this index is removed as well. Next, we can remove the auxiliary variable W_{rtk} because this variable was needed to indicate whether a recipe was produced on one of the packaging lines. If we only have one packaging line this variable W_{rtk} is equal to G_{rt}. The constraints change due to the removed indices, but no constraints are removed. For all packaging lines separately, we distinguish two models. First, a model which includes the format changeover for the five packaging lines 'U, *R, X, Y, Z'*, that can produce multiple formats. Second, a model for the remaining packaging lines that cannot produce multiple formats. Both mathematical models can be found in the appendix; model 3 and model 4. The specifications of these 14 models can be found in Table 11.

Table 11: Specifications of the sperate models

Lines included	# SKUs	# Variables	# constraints	Model Nr.
V	18	720	3,368	4
U	25	954	2,752	3
T	15	585	4,560	4
R	36	1,380	6,312	3
A	8	411	1,944	4
C	12	561	2,584	4
E+F	25	1,134	5,264	4
G+H	37	1,425	6,256	4
I+J	21	807	4,048	4
K	22	873	4,200	4
L	16	735	3,480	4
X	26	1,638	5,160	3
Y	21	1,392	4,432	3
Z	19	1,104	4,192	3

A major drawback of splitting the main model into models per packaging line is that the minimum and maximum production quantities are no longer close to reality. The minimum production quantity is in many cases achieved by combining multiple products on different packaging lines. In addition, the maximum quantity per packaging line will never be achieved at only one packaging line, although this is an important restriction within the factory. After we run all models separately, this could still be checked manually.

4.5 Conclusion

In this chapter, we have combined all gathered data on the current situation within Friesland Campina as discussed in Chapter 2 and our knowledge about lot sizing optimization as obtained in Chapter 3 to develop a tailored mixed integer linear programming model. With this approach, we answer our third research question: *"How can we develop a tactical production planning model that optimizes the cycle stock levels of all SKUs?".*

We design four different models to run all packaging lines together, in groups and with or without format changeovers. With the models for each packaging line, we hope to guarantee a problem size that can be solved towards optimality. The objective function of the model minimizes the setup costs at the product family level, setup costs at the recipe level, setup costs for changing a format on a packaging line, holding costs and capital costs. Based on this objective function, we can compare multiple drumbeat patterns and determine the settings which yield the lowest overall costs. A cost-minimizing combination of setup and inventory costs is the output of the model with the corresponding drumbeat patterns for all SKUs. In the next chapter, we will present a numerical implementation of these models comparing their results to the current practices followed.

5. COMPUTATIONAL RESULTS

In this chapter, we provide the results of the model that we developed in Chapter 4. We start by describing the verification and validation process of the pilot with packaging line *'U'* in Section 5.1. Next, in Section 5.2 and Section 5.3 we describe the input and output of the model. In the following section, we describe the numerical results of the different models that we developed. We also make some simplifications to the models to obtain a feasible solution faster. In Section 5.5. we describe the results of the models with these simplifications. In Section 5.6, we do a sensitivity analyses to measure the robustness of our mathematical model. We end this chapter with a conclusion in Section 5.7.

5.1 VERIFICATION AND VALIDATION

Before we start our computations of the model with all packaging lines together, we validate and verify our model with only one packaging line included to ensure correct and reliable outcomes. First, the reality is analysed and based on the main problem, a model is designed and written on paper. This model is then converted to a programmed model. With the verification step, we ensure that the model written on paper corresponds with the programmed model, whereas we ensure with the validation step that the programmed model represents reality accurately (Law, 2015). Figure 14 shows the verification and validation process.

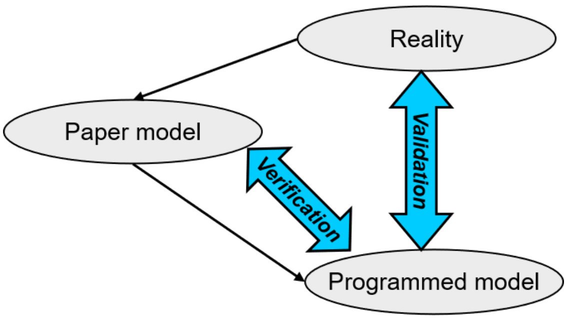

Figure 14: Verification and validation process

In the pilot, we focus on packing line *'U'* during this verification and validation process. This packaging line has many different products as well as two different formats and is therefore well suited for performing this initial verification and validation. First, we formulate the model referring to reality. We identify the setup and inventory costs with several stakeholders as explained in Chapter 2. We are regularly in contact with the Supply Network Planner, who has packing line *'U'* in her portfolio, to gather information and to validate the assumptions made. According to all this information, we design the model on paper as written in Appendix A; model 3.

Next, we convert this model into a programmed model. We use an incremental approach; after each new step added into the programmed model, we check the correctness. The complexity of the model increases with each newly added step. Therefore, we check some calculations manually to ensure that the correct references are made, and no circular and redundant steps are used. The computation time of this packaging line *'U'* model is around two minutes, which is promising for the remaining models.

In addition, we need to validate the results of the packaging line *'U'* model. We must make some minor manual adjustments to create drumbeat patterns for all products that are approved by all stakeholders. These adjustments are necessary because not every detail is and can be added to the model. As explained in Section 4.1.1, this level of detail at the product level is not considered.

Different options are often used for this validation step. The most straightforward way is to use historical data and compare the obtained tactical planning solution with the historical tactical planning. Unfortunately, this is not possible in our research. The tactical planning created by APO is not saved. Only definitive schedules are available that are manually adjusted by SNP according to the operational situations are saved. Historical planning information at the tactical level is not available and therefore we cannot make this comparison. Another option to validate our model is to run the same model but with the settings of the current situation. In Section 5.3 we explain how we can solve the model with the settings of the current situation. We are aware that this validation method is not ideal, but it is the best option available in our research. Together with minor adjustments to the drumbeat patterns and analyzing the results of the model with the current setting this model is validated and approved by the stakeholders. Moreover, the results of this single packaging line are immediately implemented. The results of this implementation will be visible in four to six weeks.

5.2 Model input

In this section, we briefly describe which data is used in the model and why decisions are made. First, we use forecasted demand and not historical data in this research. We decide to use forecasted demand because this allows us to analyze the real planning situation with the current drumbeat patterns. The drumbeats are used to create a tactical production planning, but the historical production planning data is on an operational level. Many manual adjustments are made in this planning and therefore it is not suitable for comparison with the tactical planning of our model.

Based on the safety days' supply and the forecast, we calculate the safe stock per week per product. As explained in Section 4.1, we calculate the initial inventory ourselves. This allows the model to choose a drumbeat that will only be produced in week four. The initial inventory is equal to the sum of the forecast of the first four weeks plus the safety stock of week four.

Next, the capacity of each packaging line is given in the number of shifts, which last 8 hours. Each packaging line also has its own planning speed which largely depends on the format that is produced. Furthermore, the setup times at product family level, recipe level and format level are included and also depend on the packaging line.

At the recipe level, we take into account the minimum and maximum production quantities. These are given by the resource planners and are above all the bottleneck of the entire process.

Finally, the different costs drivers are considered. On the one hand, we have the setup costs at the product family level, recipe level and format level and on the other hand, we have the inventory costs at the product level as explained in Section 2.3.

5.3 Model output

We implement the model of Section 4.2 and use the input as specified in Section 5.2. The output of our model is twofold. First, the total savings of the tactical planning based on the chosen drumbeat patterns of all products. The total costs consist of the setup and the inventory costs. Based on the drumbeat patterns, the production moments are given. When production takes place, the setup costs at the different levels are incurred. The inventory costs are calculated based on the inventory level at the end of the week. The total costs are compared with the total cost of the same model but with the drumbeat pattern settings of the current situation. These total savings of the tactical planning based on the chosen drumbeat patterns of all products is one of the outputs of our model. This allows us to quantify the impact of cost reductions. To compare the outcomes to the current situation, we insert the current drumbeat patterns in the model and run without the decision variable Q_{fn}. Some manual adjustments are made in the model, to be able to analyse the current situation. Because in the current situation not all products in one product family have the same drumbeat pattern, we change the decision variable Q_{fn} into an auxiliary variable Q_{in}. Constraint (6) is the only variable that directly depends on the decision variably Q_{fn}. We remove constraint (6) and insert a new big M constraint to indicate whether a product family is produced in a particular week to account for the corresponding setup time and costs.

The second output of our model is the list of chosen drumbeat patterns of all products. These drumbeat patterns are indicated by the decision variable Q_{fn} that has a value of 1 if the drumbeat pattern is chosen and zero otherwise. These drumbeat patterns are the actual changes that need to be made to implement the solutions found in our research. By changing the drumbeat patterns in the 'masterdata' in SAP, APO will make a planning based on these new drumbeat patterns.

5.4 RESULTS MILP

In this section, we assess the results of our mathematical model described in Section 4.2. We run the different experiments as described in Section 4.4. First, we discuss the results of the model with all packaging lines included followed by the results of the packaging lines divided into groups. Lastly in this section, we discuss the results of all packaging separately.

All test results are obtained with the COIN-OR Branch and Cut (CBC) Solver, an open-source mixed integer linear programming solver written in C++. Most of the other methods available in the OpenSolver add-in use registration, which is not allowed due to privacy statements. COIN-OR branch and cut solver is the best option within the choice to solve the model towards optimality with the OpenSolver in Microsoft Excel.

5.4.1 All packaging lines together

The model with all packaging lines included contains 12,903 variables, as shown in Table 9. Due to this enormous decision space, the computation time of this model is very high. After we run the model for twelve hours, only a fractional solution is returned. We cannot use this solution because for most of the products multiple drumbeat patterns are chosen with values between zero and one; instead of just a zero or one. Therefore, we cannot analyze this experiment any further. In Section 6.2, we elaborate further on the improvements and possibilities for this model.

5.4.2 Packaging lines divided into groups

Due to the large problem instance of the entire model, we decide to make groups as explained in Section 4.4.2. However, the number of variables in these groups is still very large for solving towards optimality. Again, for these models, we encountered problems with running these models. The first group consists of 8 packaging lines. This model still has a large decision space with 5,043 variables. After running the model of group one twelve hours, again, only a fractional solution is returned. We cannot do any analyses on this solution because no drumbeat patterns are chosen for the products on these packaging lines.

The model of group number two is based on six packaging lines and consists of 4,935 variables. This is only a fraction smaller than group two. However, in four hours a solution is found for this model, but not the optimal solution. The reason this model finds a solution can be explained by the difference in complexity of the product families in these two models. In the group one model, 37 product families must find the optimal drumbeat patterns for a total of 116 products. These product families consist of several products from multiple packaging lines. These mutual relationships increase the complexity of the model. In the group two model, 116 products depend on 57 product families. Of these 57 product families, 34 consists of only one product, making it easy to find an optimal drumbeat for that one product. The other 23 product families are more complex but contain fewer interrelations between multiple packaging lines than the product families in the group one model. So, there are more decisions, but the complexity decreases.

The model of group three consists of only three packaging lines and has 2,757 variables. We find a solution within four hours, but still not the optimal solution. In Table 12 we show a comparison of the costs between the current and the model situation. The first row is indicated red because no actual solution is found for this model. Due to this false solution, this total value presents a distorted vision of the results. The solution of the group two model gives an overall savings of 4%. Interestingly, the setup costs are higher than the current situation and the inventory costs lower. The solution of the model gives a better balance between the setup and the inventory costs. The solution of the group three model scores worse on both costs' factors.

Table 12: Comparison of the costs of the current and model situation of the three groups

Group	**SETUP COSTS**			**INVENTORY COSTS**			**TOTAL COSTS**		
	Current	*Model*	*Diff*	*Current*	*Model*	*Diff*	*Current*	*Model*	*Diff*
1			63%			18%			32%
2			-24%			20%			4%
3			-1%			-15%			-10%
TOTAL			**23%**			**9%**			**14%**

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To check the quality of the found solutions for group two and group three, we calculate the gap between the obtained solution and the relaxed LP solution. The relaxed LP solution is the lower bound of the solution quality of the original problem. When the gap with the lower bound is small, we know that the costs of the found solution are close to the optimal solution. We calculate the gap as follows:

$$(cost\ of\ found\ solution\ -\ cost\ of\ lower\ bound)\ /\ cost\ of\ lower\ bound.$$

The solution obtained during the LP relaxation will not be a feasible solution in our case and will be much different from the optimal solution. Multiple drumbeat patterns can be selected in the LP relaxation solution. We see that in every model the drumbeat patterns *1000, 0100, 0010, 0001* are chosen, with a combination around the values *0.9997, 0.0001, 0.0001, 0.0001* respectively. This is the same as the selection of drumbeat pattern *1111* with value *1*, but it makes a huge difference in the total setup costs. With the first option, setup costs are taken into account for week 1 but production in the other three weeks are almost zero. In the second option, the setup costs are taken into account for each week. Therefore, the lower bound will also be lower than the optimal solution. In the next section, we will make this comparison with the optimal solutions found.

We cannot easily generate a feasible solution from this LP relaxation solution. We could say that the drumbeat pattern with the highest value between one and zero (0.9997) is the most likely drumbeat pattern to choose. However, is it not possible to choose only drumbeat patterns for all SKUs with one production moment every four weeks. On the other hand, we can say that the week chosen to produce will probably be in the drumbeat pattern of the optimal solution. This can limit our drumbeat patterns options in the model.

In Table 13 we show the gap with the lower bound for group two and group three. Group one has not been included, because we have not found a feasible solution with the model of group one. The total costs for both group two and group three are higher than the lower bound. As explained above, this is not surprising. However, the gap is very large for both solutions. Therefore, we can assume that it is likely that we will find a better feasible solution if we make some adjustments to the model. Finding the optimal solution is likely because of the large gap.

Table 13: Quality of the obtained solution of group two and three

Group	**TOTAL COST**		
	Lower bound	*Model*	*Gap (%)*
2	*CONFIDENTIAL*		**66%**
3			**82%**

5.4.3 All packaging lines separately

To reduce the computation time, even more, we split the models into 14 separate models as described in Section 4.4.3. We found a solution within 2 minutes for packaging line '*U*' during the pilot. However, we did not find a solution for all packaging lines separately. After we ran the model of packaging line '*R*' for twelve hours, we did not find any feasible solution until then. For two other packaging lines 'E+F & G+H' we only found a feasible solution after four hours. For the other packaging lines, an (optimal) solution was found within four hours. In the table below we show an overview of the solutions found per packaging line. Because no solution was found for packaging line '*R*', we have not included this packaging line in the following analyses.

Table 14: Solutions found per packaging lines

Line	**Optimal solution**	**A feasible solution**	**No solution**
V	X		
U	X		
T	X		
R			X
A	X		
C	X		
E+F		X	
G+H		X	
I+J		X	
K	X		
L	X		
X	X		
Y	X		
Z	X		

From the models with all packaging lines separately, we receive good results that we can analyze. First, we compare the costs of the current situation against the costs generated by the models. In addition, we look at the chosen drumbeat patterns and how they differ from the drumbeats currently used. Finally, we also look at the capacity of the packaging lines and how this is distributed over the weeks.

In Table 15 we show an overview of the costs of the current situation and the results of the models per separate packaging line. For each packaging line, we show the setup, inventory and total costs of the current situation and our mathematical models followed by the savings in percentage. Only for packaging line '*C*', the setup costs are higher than the current solution. The total savings on setup costs can be 24%. The inventory costs are higher at four packaging lines. However, by the total savings at the other packaging lines, the savings on inventory costs can still be 2%. In the last column, we see that the total savings for each packaging line are positive and that the total savings can be 10%. By combining these solutions from the separate packaging lines models, we do not obtain a feasible solution because one constraint is violated. The total cream production quantities are above the maximum cream production quantities. We will discuss this violation in more detail later at the end of this section.

Table 15: Comparison of the costs of the current and model situation of the separate packaging lines

LINE	**SETUP COSTS**			**INVENTORY COSTS**			**TOTAL COSTS**		
	Current	*Model*	*Diff*	*Current*	*Model*	*Diff*	*Current*	*Model*	*Diff*
V			66%			-7%			33%
U			19%			15%			16%
T			10%			9%			10%
A			27%			-9%			4%
C			-9%			8%			2%
E+F			7%			4%			5%
G+H	CONFIDENTIAL		27%	CONFIDENTIAL		-9%	CONFIDENTIAL		4%
I+J			22%			5%			10%
K			11%			7%			9%
L			33%			-3%			14%
X			2%			10%			7%
Y			0%			7%			4%
Z			0%			2%			1%
TOTAL			**24%**			**2%**			**10%**

As done in the previous section, we check the quality of the obtained solutions above with the calculated lower bound of each packaging line. The lower bound solutions are again far from any solution due to the multiple drumbeat patterns chosen as explained in Section 5.4.2. Table 16 shows the gaps for all thirteen models for which we find an optimal and/or feasible solution. Only for packaging lines 'E+F & G+H', we did not find an optimal solution in four hours, but for all other packaging lines, the model solution is the optimal solution. Still, these values are far from the lower bound. It is not possible to do a very good analysis of the quality with these lower bounds. However, we can say that on average a gap of 37% will be quite close to the optimal solution.

Table 16: Quality of the obtained solution of the models for each packaging line separately

Line	**TOTAL COST**		
	Lower bound	*Model*	*Gap (%)*
V			**30%**
U			**38%**
T			**39%**
A			**43%**
C			**46%**
E+F			**33%**
G+H			**24%**
I+J			**38%**
K			**67%**
L			**57%**
X			**29%**
Y			**39%**
Z			**41%**
TOTAL			**37%**

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Next, we look at the drumbeat patterns currently used against the chosen drumbeat patterns in our mathematical models. In Table 17 we show the changes in the drumbeat patterns of all 265 products analyzed. First, we count the number of drumbeat patterns that remain the same. So, for 47 products it is not necessary to change the drumbeat patterns. For the majority, 131 products, the number of productions remain the same, but the pattern is different. So, for example, product X has currently a drumbeat pattern of *1000*, but in our mathematical model, the solution gives product X a drumbeat of *0010*. Moreover, we count the number of products for which the chosen drumbeats pattern has more and fewer production moments than in the current situation.

Table 17: Changes of the drumbeat patterns

LINE	**DRUMBEAT PATTERNS**		**NUMBER OF PRODUCTIONS**		
	Same	**Different**	**Equal**	**More**	**Less**
V	5	13	10	0	8
U	3	22	11	13	1
T	4	11	9	2	4
A	3	5	6	0	2
C	1	11	5	4	3
E+F	8	17	13	6	6
G+H	6	31	27	3	7
I+J	1	20	9	3	9
K	2	20	4	13	5
L	4	12	10	0	6
X	5	21	9	17	0
Y	0	21	3	18	0
Z	5	14	15	4	0
TOTAL	**47**	**218**	**131**	**83**	**51**

So, on the setup cost can be a saving of 24% and on the other hand, 32 products (83-51) will have more production moments. This can be explained by the product families that are used in our mathematical model. To combine the products that do not require a setup one after the other, these setup costs can be saved. Therefore, we can conclude that it is mainly possible to reduce the setup costs by cleverly combining the products into product families.

Furthermore, we look at the different capacity constraints in our model. First, we evaluate the capacity utilization of each packaging line. In the table below we show the changes in the capacity utilization in percentages. So, the average current capacity utilization of packaging line 'V' is 59% and with our model, the average capacity utilization drops to 55%. For packaging line '*T*', the average capacity utilization remains the same. However, in the solution of our model, the capacity utilization of this packaging line is more evenly distributed over the weeks. For four packaging lines, the average capacity utilization is slightly higher than in the current situation. The total capacity utilization can be reduced by 3% over all packaging lines.

Table 18: Change in capacity utilization in percentages

Line	**CURRENT CAPACITY USE**				**CAPACITY RESULTS MODEL**				**Average savings**
	Week 1	Week 2	Week 3	Week 4	Week 1	Week 2	Week 3	Week 4	
V									4%
U									2%
T									0%
A									3%
C									-2%
E+F									1%
G+H									5%
I+J									19%
K									11%
L									4%
X									-1%
Y									-2%
Z									-1%
TOTAL									**3%**

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Second, we evaluate if the minimum and maximum production quantities are not violated. These are both constraints in all models. Since we obtain a feasible solution, we could say that both constraints are not violated. This applies to the minimum production quantities because in each model the production quantities meet the minimum. According to FrieslandCampina, several packaging lines are dependent on each other to meet the minimum production quantities. These models show that it is possible to produce all products independently while respecting the minimum production quantity.

On the other hand, we cannot say that the constraint about the maximum production quantity is not violated. The total production quantities of all separate models may exceed maximum production quantities. To analyze these maximum production quantities, we add up the production amounts per category of all recipes across all models. In Table 19 we show a in which week which category is above the maximum production quantity with a one. There is only a problem with producing cream every other week. The production of cream is not evenly distributed over the weeks. In the other weeks, the maximum production quantity for cream is not met yet. Since we evaluate all packaging lines separately, this constraint is not violated in those models, but the total cream production over all packaging lines is violated. Therefore, combining these solutions generate an unfeasible solution.

We see that the average production of cream over these eight weeks is 109%, which means that the total production of cream is higher than the maximum production quantity. This is can be explained by the fact that the minimum production quantity is met for each production in all models. If the minimum production quantities are allocated in one model with all packaging line, the total production quantities will be lower. From this analysis, we cannot state if the maximum production quantity is large enough for the total production demand because in each separate model the minimum production quantity is met which results in high production quantities.

Table 19: Percentages of maximum production quantities used in the models

Recipe category	**Maximum**	**W5**	**W6**	**W7**	**W8**	**W9**	**W10**	**W11**	**W12**
Milk	CONFIDENTIAL	0	0	0	0	0	0	0	0
Evap		0	0	0	0	0	0	0	0
Buttermilk		0	0	0	0	0	0	0	0
Flavoured Milk		0	0	0	0	0	0	0	0
Cream		1	0	1	0	1	0	1	0
CCM		0	0	0	0	0	0	0	0

Due to the violation of the maximum production quantities of cream, combining the solutions of all packaging line models separately generates an unfeasible solution.

5.5 SIMPLIFICATIONS OF THE MODEL

With the experiments done above, we still not obtain a feasible solution for every modelling option. To enlarge the possibility of obtaining a feasible solution in a reasonable time, we can simplify the model. These experiments are done with the three groups that we made in Section 4.4.2. Only for groups two and group three, we found a feasible solution but the solution of group three was worse than the current situation. In these groups, the minimum and maximum quantities are considered in a better way than analysing all packaging lines separately. In this section, we simplify the model in two different ways, combine the two options and compare the results.

5.5.1 Reducing the drumbeat pattern options

Currently, there are 12 different drumbeat patterns stored in the 'masterdata' in SAP, as we described in Section 2.6.1. By combining zero and one at four different places, we can make 15 different drumbeat patterns. However, as described in the analysis of the drumbeat patterns in Section 2.6.1, only 7 drumbeats are used by 93% of all articles. These drumbeat patterns are: *1111, 1010, 0101, 1000, 0100, 0010, 0001*. To reduce the decision space of the model, we run the models of the three groups again with only these seven drumbeat patterns.

After running each model for four hours, we find a feasible solution for each group. So, reducing the drumbeat pattern options already gives the advantage that we find a feasible solution for all three groups. In Table 20 we show a comparison of the costs between the current and the model (LD) situation, the latter refers to the models in which fewer drumbeat patterns are integrated. Although we find a feasible solution for group one, we did not find a better solution than the current situation. On the other hand, for group two and three we did find a better solution, 2% and 5% better, respectively. With these two models, the savings are mainly on the inventory costs. Due to the solution found for group one, the overall savings is negative.

Table 20: Comparison of the costs of the current and model (LD) situation of the three groups

Group	SETUP COSTS			INVENTORY COSTS			TOTAL COSTS		
	Current	*Model (LD)*	*Diff*	*Current*	*Model (LD)*	*Diff*	*Current*	*Model (LD)*	*Diff*
1	CONFIDENTIAL		-4%	CONFIDENTIAL		-11%	CONFIDENTIAL		-9%
2			-19%			13%			2%
3			0%			7%			5%
TOTAL			**-6%**			**-1%**			**-3%**

If we analyze the capacity utilization of each packaging line, we see that the average capacity utilization of seven packaging lines is slightly higher. The capacity utilization for one packaging line remains the same and for six packaging lines, the capacity utilization is lower than in the current situation. This results in savings of 2% on the average capacity utilization. An overview of the capacity utilization of each packaging line can be found in Appendix B.

In addition, we analyze whether the constraint of the maximum production quantities is being violated. The average production of cream is again 109%, which means that the total cream production from all packaging lines is higher than the maximum production quantity that is available. This also has the do with the minimum production quantity that is met in each of the three models. The total production quantity of cream can be lower if more packaging lines can be combined in one model. If we can combine more packaging lines in one model, the constraint of the maximum production quantities can also be better controlled. An overview of the results of the violations of the maximum production quantity of the recipe categories can be found in Appendix B.

5.5.2 Remove the integer constraint of the production quantities

Another simplification of the model is to remove the integer constraint of the production quantity X_{it}. As mentioned in Section 4.2.5, we consider the production quantities as integers in our model because these production quantities are in FILL, which is equal to one SKU. These production quantities must be integers, as half SKUs cannot be produced. However, due to the large production quantities, it makes little difference to planning and total costs whether one SKU is produced more or less. Afterwards, these real numbers can be rounded to get a feasible solution.

For the model of group one, this means that we remove the integer constraint for 2,784 variables from the total 5,043 variables. These 2,784 variables become reals which makes it easier to solve the problem in a reasonable time. As we did not find a feasible solution after 12 hours with the original model, we now find a feasible solution within 5 minutes. We still ran the model for four hours and the obtained solution is way better than in de the model (LD), but still slightly worse than the current solution. Also, for group two and three the running time decreases drastically to find a feasible solution. We can remove the integer constraint for 2,748 variables from the total 4,935 variables of group two. In the model of group three, we can remove the integer constraints for 1,656 variables from the total 2,757 variables of the original model. For group two and group three we find the best solution so far in our research after four hours. The results in Table 21 are obtained after running the model for four hours and with the model (NI) we refer to the models in which no integer constraint is used for the production quantities. The overall savings on the total costs can be 4%. In the solutions found, only 2 production quantities in group one and only 2 production quantities in group two are no integers. When we round these values to obtain a feasible solution, the impact on the total costs will be minimal. The savings on the total costs can be 4%

Table 21: Comparison of the costs of the current and model (NI) situation of the three groups

Group	SETUP COSTS			INVENTORY COSTS			TOTAL COSTS		
	Current	*Model (NI)*	*Diff*	*Current*	*Model (NI)*	*Diff*	*Current*	*Model (NI)*	*Diff*
1			-4%			0%			-1%
2	CONFIDENTIAL		4%	CONFIDENTIAL		15%	CONFIDENTIAL		11%
3			5%			7%			6%
TOTAL			**0%**			**5%**			**4%**

Next to the savings on the total costs, we can decrease the average capacity utilization from 66% to 64%. Of the fourteen packaging lines, the capacity utilization of 8 packaging lines is increasing. For the other six packaging lines, we see a decrease in capacity utilization. Moreover, the distribution over the weeks is better in the results of the models (NI) than in the current situation. An overview of the capacity utilization for each packaging line can be found in Appendix C.

In addition, we check the maximum production quantity of all categories. We see a different pattern where the first two weeks violate the maximum production quantity of the cream production and the other two weeks are below the maximum production quantity. However, the average production of cream over eight weeks is still 109%, as we have seen with the previous solutions. The drumbeats for the SKUs with recipes in the cream category should be manually checked and better distributed over the weeks. It seems that the maximum production quantity is not high enough to produce all cream recipes, but in our model, the minimum production quantity must always be met. If we could run all packaging lines together in one model, a better balance could be found for the cream recipes. An overview of the results of the violations of the maximum production quantity of the recipe categories can be found in Appendix C.

5.5.3 Combination of both options

Due to the promising results in the two previous sections in which we reduced the drumbeat pattern options and removed the integer constraint for the production quantities, we analyse the results if we combine these two options. We run all three models for four hours and obtained a feasible solution for all three groups. Table 22 shows the comparison of the costs between the current situation and the models (LD+NI), which refer to the models in which fewer drumbeat patterns are integrated, and no integer constraint is included. The most savings can be made on the setup costs with 14%, against 5% savings on inventory costs. In the last column, we see that the total savings for each group are positive and that the total savings can be 8%.

Table 22: Comparison of the costs of the current and model (LD+NI) situation of the three groups

Group	SETUP COSTS			INVENTORY COSTS			TOTAL COSTS		
	Current	*Model (LD+NI)*	*Diff*	*Current*	*Model (LD+NI)*	*Diff*	*Current*	*Model (LD+NI)*	*Diff*
1			17%			0%			5%
2	CONFIDENTIAL		14%	CONFIDENTIAL		16%	CONFIDENTIAL		12%
3			6%			9%			8%
TOTAL			**13%**			**6%**			**8%**

In the solutions of the three groups, we see that only 2 production quantities in both group one and group 2 are not integers. Rounding these four values, we obtain feasible solutions for all three groups. To check the quality of these obtained solutions, we recalculate the gap between the lower bound and the obtained solution, see Table 23. The gaps are still quite large but as explained in Section 5.4.2, the optimal solution will always be greater than the lower bound. Compared to the first solution found with the original model, the gap is reduced by 19% for group 2 and by 29% for group 3. Compared to the average gap of 37% of the optimal solutions of the separate packaging line models, these gaps do not seem too bad. However, these are just assumptions and not hard conclusions.

Table 23: Quality of the obtained solution of the models (LD+NI)

Group	**TOTAL COST**		
	Lower bound	*Model (LD+NI)*	*Gap (%)*
1			**40%**
2	CONFIDENTIAL		**47%**
3			**53%**

In Appendix D we provide the capacity utilization in percentages for all packaging lines. In comparison to the two options separately, which both have an average capacity utilization of 64%, the average capacity utilization in this experiment is 62%. Which is 4% lower than the current situation. The first three weeks have almost the same capacity utilization of 63%, 65%, and 64% respectively. Week four has a capacity utilization of 56%. In the current situation, the capacity utilization of the four weeks is further apart.

We also check the maximum production quantity of all categories for these models. We see the same pattern as the original model in which all uneven weeks violate the maximum production quantity constraint. However, the percentages are lower in our solution of the models (LD+NI) than the solution of the original models. The average production of cream over eight weeks is 103%, which means that the total production of cream from all packaging lines is higher than the maximum production quantity that is available. Still, manually adjustments have to be made to tackle this problem. The minimum production quantity that must be met, can be combined in reality over more packaging lines than in these models separately. For this reason, the actual production quantities could be lower. An overview of the results of the violations of the maximum production quantity of the recipe categories can be found in Appendix D.

5.5.4 Simplifications & improvements applied to the model with all packaging lines

The previously described simplifications of the model provide a feasible and better solution in a reasonable time for the models of the three groups. The step to a model with all packaging lines included is still large. To make it more likely that we will obtain a feasible solution in a reasonable time we do a step towards column generation. The idea of column generation is to consider only a subset of variables when solving the problem. Column generation leverages this idea to generate only the variables which have the potential to improve the objective function. This method is not fully implemented in this research, but we make a first step. Given the solutions in the previous sections, we see that the drumbeat patterns mostly differ in order and not in the number of productions. This idea is taken into account when solving the model with all packaging lines included along with the reduced number of drumbeat patterns and the removed integer constraint of the production quantities.

First, we analyze the drumbeat patterns of the product families of the solutions in Section 5.5.3. If drumbeat pattern *0001* is chosen for a product family, the product family will likely have drumbeat pattern *1000, 0100, 0010,* or *0001* in the optimal solution. So, we create two subsets in our model with all packaging lines included to reduce the drumbeat pattern options even more. If a product family has a drumbeat pattern with only one production moment in the solution in Section 5.5.3, this product family can only choose between the four drumbeat patterns with only one production moment in our model with all packaging lines included. On the other hand, if a product family has a drumbeat pattern with two or four production moments in the solution in Section 5.5.3, this product family can only choose between three drumbeat patterns; *1111, 1010,* or *0101*. This results in 48 product families that can choose between four drumbeat patterns and 73 groups that can only choose between the three drumbeat patterns.

Due to these simplifications and improvements, we find a feasible solution for our model with all packaging lines included after four hours. Table 24 shows the results of the model in comparison with the current situation. With this solution we could realize a saving of 9% on the total costs. The most savings can be made on the setup costs with 7%, compared to 4% savings on inventory costs.

Table 24: Comparison of the costs of the current and model situation with all packaging lines included

Line	**SETUP COSTS**			**INVENTORY COSTS**			**TOTAL COST**		
	Current	*Model*	*Diff*	*Current*	*Model*	*Diff*	*Current*	*Model*	*Diff*
All	*CONFIDENTIAL*		7%	*CONFIDENTIAL*		4%	*CONFIDENTIAL*		9%

To check the quality of our obtained solution, we compare the total costs of the model with the total costs of the LP relaxation solution. Table 25 shows the results of this comparison. The gab is still 40%, but as we have seen with the optimal solutions found for the models with one single packaging line, the average gab is 37%. Therefore, this gab is not too bad. However, this is just an assumption and not a hard conclusion.

Table 25: Quality of the obtained solution of the model with all packaging lines included

Line	**TOTAL COST**		
	Lower bound	*Model*	*Gap (%)*
ALL	*CONFIDENTIAL*		**40%**

In addition, we check the capacity utilization in percentages for all packaging lines, which can be found in Appendix E. The average capacity utilization of this solution is 61%, which is 5% lower than in the current situation. For nine of the 14 packaging lines, the capacity utilization is lower than in the current situation. For two packaging lines, the capacity utilization remains the same and for the other three, the capacity is slightly higher.

Next, we check the maximum production quantity of all categories for each category. Because all packaging lines are included in one model, the maximum production quantity cannot be violated anymore. We see therefore that in almost every week 100% of the maximum production quantity of cream is utilized. This gives us an extra insight that the demand for SKUs with cream recipes is close to the limit of the plant. The average production of cream over eight weeks is 99%. An overview of the results of the violations of the maximum production quantity of the recipe categories can be found in Appendix E.

Due to the radical approach of cutting out drumbeat pattern options, we do not check in detail the changes in the drumbeat patterns. From the 121 product families, 73 product families, which are 191 SKUs, can only choose between only three drumbeat patterns. Therefore, we can already expect a lot of changes in the drumbeat patterns as twelve different drumbeat patterns are currently used.

5.6 Sensitivity Analysis

We perform a sensitivity analysis on the input parameters we have estimated to check the robustness of the drumbeat decisions made in our mathematical model. We analyse the sensitivity of the results concerning the setup costs, inventory costs and the forecast. Taking the computation time of the models into account, we perform this sensitivity analysis only on the original model of packaging line '*U*', as described in Appendix A; model 3. So, no simplifications as described above are considered. Due to the pilot with this packaging line, this model is most validated and therefore most suitable.

5.6.1 Sensitivity of setup & inventory costs

As explained in Section 2.3, we made several assumptions while determining the setup and inventory costs. The actual costs can differ from our estimations and therefore we do a sensitivity analysis to check the robustness of our model. The ratio between the setup and inventory costs is a very important input parameter. To test the sensitivity of the setup and inventory costs, we change the setup and inventory costs with different percentage combinations. We find for each new combination the optimal solution within 5 minutes. We compare the results with the optimal solution found in the original settings. In Table 26 we show the results on the different cost indicators of the sensitivity analysis.

Table 26: Results of the sensitivity analysis based on the ratio between setup and inventory costs

Change in setup costs	***Change in inventory costs***	**Setup costs**	**Difference with base**	**Inventory costs**	**Difference with base**	**Total costs**	**Difference with base**
0%	***0%***		**0%**		**0%**		**0%**
-10%	*0%*		8%		-6%		-2%
-10%	*+5%*		-25%		10%		3%
-10%	*+10%*		-3%		8%		5%
-5%	*0%*		-18%		4%		-2%
-5%	*+5%*		10%		1%		4%
-5%	*+10%*		-8%		12%		7%
0%	*-10%*		0%		-11%		-8%
0%	*-5%*	*CONFIDENTIAL*	0%	*CONFIDENTIAL*	-5%	*CONFIDENTIAL*	-4%
0%	*+5%*		0%		4%		3%
0%	*+10%*		10%		5%		7%
+5%	*0%*		5%		-2%		0%
+5%	*-5%*		-23%		5%		-2%
+5%	*-10%*		-8%		-6%		-6%
+10%	*0%*		16%		-1%		4%
+10%	*-5%*		8%		-5%		-1%
+10%	*-10%*		-4%		-4%		-4%

The first row represents the solution found with the original settings. By only reducing the setup or inventory costs by 5% or 10%, the total costs are between 2% and 8% lower than the original solution. Remarkably, when we only reduce the inventory costs, the setup costs remain almost the same and the savings is only in the inventory costs themselves. By only increasing the setup or inventory costs by 5% or 10%, the total costs are between 0% and 7% higher than the original solution. We see that the changed percentages are higher than the impact on the total costs.

If we reduce the setup costs and increase the inventory costs, so that the difference becomes greater, the total costs increase by a percentage between 3% and 7%. On the other hand, if we do the opposite and increase the setup costs and reduce the inventory costs, the total costs are between 1% and 6% lower than the original solution. So, if the inventory costs are lower than the setup costs, this has a positive effect on the total costs. The impact on the total costs is always smaller than the changes made in the setup and/or inventory costs.

In addition, we check the changes in the drumbeat patterns based on the ratio between the setup and inventory costs. In Table 27 we give an overview of the changes in the drumbeat patterns due to the changes in the setup costs. This analysis is done at the SKU level. It is not possible to do this comparison at the product family level because the product families are made in this research and not all SKUs in one product family follow the same drumbeat pattern. Therefore, we do the comparison between the current drumbeat patterns and the drumbeat patterns of the solution of our models at the SKU level. First, we check how many drumbeat patterns remain the same. Next, we monitor the number of productions. Are they the same with perhaps the exact same drumbeat or are there more or fewer production moments in the obtained planning? The first row represents the solution with the original input variables, for which of the drumbeat patterns are for all 25 SKUs the same and so the number of productions is the same.

Table 27: Changes in the drumbeat patterns based on the ratio between setup and inventory costs

Change in setup costs	***Change in Inventory costs***	**DRUMBEAT PATTERN**		**NUMBER OF PRODUCTIONS**		
		Same	**Different**	**Equal**	**More**	**Less**
0%	***0%***	**25**	**0**	**25**	**0**	**0**
-10%	*0%*	9	16	13	12	0
-10%	*+5%*	14	11	25	0	0
-10%	*+10%*	5	20	23	2	0
-5%	*0%*	14	11	21	0	4
-5%	*+5%*	0	25	21	4	0
-5%	*+10%*	4	21	13	2	10
0%	*-10%*	2	23	25	0	0
0%	*-5%*	2	23	25	0	0
0%	*+5%*	16	9	25	0	0
0%	*+10%*	13	12	15	10	0
+5%	*0%*	16	9	25	0	0
+5%	*-5%*	5	20	11	0	14
+5%	*-10%*	2	23	15	0	10
+10%	*0%*	14	11	23	2	0
+10%	*-5%*	14	11	25	0	0
+10%	*-10%*	0	25	21	0	4

If we only change the inventory costs, we see almost no differences. Only if we increase the inventory costs by 10% will 10 products shift to more production moments with a different drumbeat pattern. This seems like a lot of changes, but these 10 products are in the same product family and thus follow the same drumbeat. It is becoming more attractive to perform a setup more often than to have many products in stock. That is why we see that production is more frequent if we increase the inventory costs by 10%. If we only change the setup costs, we see a little bit more changes in the production patterns. Despite the 10 products in one product family, we see little changes in the number of productions. Most drumbeat patterns only shift in their production sequence. Changes in both setup and inventory costs result in minor changes in the number of productions as well. However, many drumbeat patterns shifted in their sequence.

5.6.2 Sensitivity of forecast

All the calculations are based on the forecast that is created by the demand planners. However, the actual demand can differ from the forecast made. In this section, we analyse the robustness of our mathematical model against the changes in this forecast. Table 28 shows the results of this sensitivity analysis. We see only minor differences in the setups costs when we change the forecast in our mathematical model. The inventory costs do change, which makes sense because we need fewer or more products in stock due to the changes in the forecast. Changes in the forecasts result only in small differences in the total costs.

Table 28: Results of the sensitivity analysis based on forecast

Change in forecast	**Setup costs**	**Difference with base**	**Inventory costs**	**Difference with base**	**Total costs**	**Difference with base**
-10%	CONFIDENTIAL	1%	CONFIDENTIAL	-9%	CONFIDENTIAL	-6%
-5%		2%		-2%		-1%
Base		0%		0%		0%
+5%		0%		3%		3%
+10%		-1%		9%		6%

In addition, we analyse the differences in the drumbeat patterns, see Table 29. The drumbeat patterns do change as well, but in three of the four cases, only the order of the chosen drumbeats change. If we decrease the forecast by 5%, the drumbeat patterns differ for 14 products in the number of productions. Again, these 10 products follow the same drumbeat because of the relationship in the product family. Only one drumbeat pattern has changed at the product family level.

Table 29: Changes in the drumbeat patterns in the sensitivity analysis based on forecast

Change in forecast	**Same drumbeat**	**Equal # productions**	**More # productions**	**Less # productions**
-10%	2	25	0	0
-5%	2	11	10	4
Base	-	-	-	-
+5%	18	25	0	0
+10%	18	25	0	0

5.7 Conclusion

This chapter compares the results of the different experiments as proposed in Chapter 4 against the current situation. With these analyses, we answer our fourth sub-question: *"How does the proposed planning tool perform?"*.

In the first option, we test the model with all packaging lines included. Because of the enormous decision space, no solution can be found within twelve hours. In the second option, we split the model into three subgroups, with each a set of packaging lines. However, these models are still large with several thousand variables. In one of the three cases, no solution can be found within twelve hours. A good analysis of this option is therefore not possible. In the third option, we evaluate all packaging lines separately. Only for packaging line '*R*', no solution can be found within twelve hours. For all the other packaging lines we found an (optimal) solution within four hours. The total savings on all these packaging lines can be 10% of the total costs. The total capacity of all packaging lines can be reduced by 7%. Each packaging line meets the minimum production quantity constraint, which indicates that the packaging lines are less dependent than assumed by FrieslandCampina. However, the combination of these solution is not a feasible solution because the maximum production quantity of cream is violated.

By doing some simplifications and improvements within the model, we manage to find a solution for our model with all packaging lines included within four hours. Analysis shows that savings of 7% on setup costs and 4% on inventory costs can be achieved. The total costs can be reduced by 9%. The average capacity utilization can be reduced by 5% and the maximum production quantity is not violated. Therefore, we found a feasible solution with a positive savings on both the costs and the capacity utilization within the plant.

The sensitivity analysis tells us that our mathematical model is not very sensitive to changes in setup costs, inventory costs or forecast. When changing the ratio of setup and inventory costs, the total costs do not differ by more than 8%. There are some minor changes in the chosen drumbeat patterns, but most of them are just switches in the drumbeat pattern order. Changing the forecast results in a deviation of at most 6% and again mostly switches in the order of the drumbeat pattern. So, we can conclude that the chosen number of productions is robust, but that the specific drumbeat patterns may differ in sequence.

In general, we see that the overall number of productions of all products is increased but the total setup costs can be reduced. Therefore, we can conclude that the optimization is mainly driven by cleverly combining products and merging them into one product family to reduce the number of setups.

6. CONCLUSIONS AND RECOMMENDATIONS

In this final chapter, we report our main conclusions and recommendations acquainted with this research. First, in Section 6.1, we discuss the most relevant conclusions of our research. Next, we discuss the recommendations that are split into general recommendations and recommendations focused on the implementation of the model in Section 6.2. Furthermore, we address some points for discussion in Section 6.3. In the final section, we discuss several topics that require further research.

6.1 CONCLUSIONS

The goal of this research is to answer the main research question: *"How can FrieslandCampina optimize costs between setup and inventory of the plant in Aalter by developing a tactical production planning tool using the optimal cycle stock levels and drumbeat patterns of all SKUs?"*. The best method found to make an optimal trade-off between the setup and inventory costs, taking into account the capacity constraints and the dynamic demand, is the Capacitated Lot Sizing Problem. In this research, we have made a mathematical model which is based on the CLSP with all the details of the plant in Aalter integrated. By doing several experiments with different settings we obtained feasible solutions and, in some cases, even optimal solutions. In the remainder of this section, we address the relevant remarks and findings gained throughout our research, ranked by relevance.

- The model with all packaging lines included is the best representation of the plant in Aalter. The best solution found with this model results in saving of 9% on the total costs. With this solution, we can reduce the setup costs by 7% and the inventory costs by 4%.
- The average capacity utilization over all weeks and all packaging lines can be reduced by 5%.
- The overall number of production moments of all products can be increased while the total setup costs can be decreased. Therefore, we can conclude that the optimization is mostly driven by cleverly combining products and merging them into one product family to reduce the number of setups.
- By reducing the drumbeat pattern options and removing the integer constraint of the production quantities from the original model, we obtain a feasible solution for all models.
- The bottleneck in the production process of the plant is the preparation of the cream recipes, which is bounded to a maximum production quantity. On average is 99% of the maximum production quantity produced every week.
- It is possible to run all packaging lines separately without violating the minimum production quantity constraint. This means that the packaging lines are less dependent than is assumed by FrieslandCampina.
- The sensitivity analysis shows that our model is robust. The deviations of the total costs are between 0 and 8%, while we changed the input parameters by 5% or 10%. By changing the ratio between setup and inventory costs or the forecast, the number of productions remains almost the same. However, the drumbeat patterns differ in order. This again indicates that the optimization is mainly driven by cleverly combining products when the production moments are indicated.
- The model is a good representation of the current situation. However, the use of the OpenSolver results in a high run length of the models.

- The run length of the models increases exponentially. For the original models, we have found no feasible solution for the model with all packaging lines, the model of group one, and packaging line *'R'* within 12 hours.
- The product families are created together with the stakeholders and the Supply Network Planners of FrieslandCampina. The drumbeat patterns are assigned to these product families and therefore play a crucial role in the mathematical model. Changes in these product families will impact both the planning and total costs.
- The solutions of the LP relaxation are not so helpful in our research. Due to drumbeat patterns that can be chosen, the setup costs are incurred for one of the four weeks only, resulting in a lower bound that is far from the optimal solution. Although we saw that removing several drumbeat pattern options and removing the integer constraint of the production quantities drastically reduced the optimality gap.
- The tool provides a great insight into the optimal drumbeat patterns for all packaging lines, but manual adjustments and validations are still needed before the results can be implemented.
- Determining the setup and inventory costs was time-consuming and difficult. We made several assumptions and the costs are still estimates. Especially the setup costs are hard to determine because little information is available.

6.2 Recommendations

We provide several recommendations for the utilization of the optimization tool. We make a distinction between general recommendations and recommendation for implementing and using the optimization tool.

6.2.1 General recommendations

In this section, we provide general recommendations which focus on the model, the results and the input data, ranked by relevance.

- A major drawback of the model is the run length, which makes the model not very suitable for FrieslandCampina to use while determining drumbeat patterns for all SKUs. We recommend converting the mathematical model into another program, such as CPLEX or AIMMS. Another option is to make use of heuristics to generate a (near) optimal solution. As As discussed in our literature review, simulated annealing shows promising test results in other CLSP research. This could be done in VBA or another preferred program can be selected. In addition, the heuristic algorithm column generation can solve the mathematical problem of our research by generating a decomposition of the problem into a master problem and subproblems. This research takes a first step towards column generation by using two subsets of the drumbeat patterns options. Research should be done on the results of a heuristic compared to an algorithm such as column generation in order to make a good conclusion about which heuristic or algorithm is most appropriate. From the results of our research, we can conclude that the complex production planning of the plant in Aalter results in a large computation time with the OpenSolver in Microsoft Excel. Moreover, data manipulation in Microsoft Excel is very time-consuming. When a new product is introduced or a product is no longer produced, many steps are required. There is a good chance that an error will be made. This is yet another reason to switch to a different program or a heuristic approach.

- The production of cream in each week is almost equal to the maximum production quantity of cream of the plant in Aalter. Therefore, we recommend analyzing the process of cream production and identify possible improvements. Increasing the maximum production quantity of cream gives more possibilities to combine different drumbeat patterns which in turn can lead to a higher saving on the total costs.
- Compiling the product families has a major influence on the generated results. The product families of packaging line *'U'* are extensively verified with the supply network planners. We would advise FrieslandCampina to do this same verification extensively for the other packaging lines.
- The calculations in the model are based on input data. The setup and inventory costs are gathered and estimated as we discussed in Section 2.3. We advise FrieslandCampina to collect the input data to increase the accuracy of the decisions made by the model. Collecting this data would not only lead to cost savings by implementing this accurate input data in our model but also helps with monitoring these costs drivers and detect potential outliers.
- The model does not take the distribution of the capacity over the various weeks into account. FrieslandCampina can tackle this problem in two different ways. First, two additional constraints can be added to establish the desired minimum and a desired maximum to the capacity each week. However, they could also choose to use the found (optimal) solutions and swap some drumbeat patterns to generate a more evenly distributed capacity while monitoring the total costs.
- FrieslandCampina has a lot of software tools to look ahead in production planning schedules and to perform analyzes based on these schedules. However, almost no historical data about production planning schedules are available. We advise FrieslandCampina to collect the production planning generated by the planning tool APO. With this historical data, it is possible to analyze the bottlenecks and adjust the drumbeat patterns based on those analyses. Now, this information is lost because manual adjustments are made in the planning and cannot be traced back.

6.2.2 Implementation recommendations

In this section, we provide several recommendations focused on the implementation of the model within the planning processes of the plant in Aalter, ranked by relevance.

- As described in Section 5.1, we implemented the results of the pilot packaging line '*U*'. We recommend waiting and analyzing the results of this packaging line first. If all results are positive and the results are as expected, the drumbeat patterns of the other packaging lines can be validated and implemented.
- Before implementing the results of our research, it is necessary to validate the results with the various stakeholders; demand planners, supply network planners, schedulers and production managers.
- Currently, the production schedule generated by APO is not monitored. This information is valuable for our research and for changing the existing drumbeat patterns. We, therefore, recommend starting to collect these production planning schedules to monitor whether the expectations, as proposed in this research, are being met.
- Finally, appoint someone as the key user of the model. For this project to be successful, the model must be owned by a person who strives to implement it and repeat it semi-annually.

6.3 DISCUSSION

In this discussion, we address the largest improvement suggestions for our model and this research.

- During this research, we did not have access to the information systems of FrieslandCampina. Gathering information was always done via a colleague. Eventually, I gathered all information that I needed, but due to this way of working it sometimes took a long time.
- As mentioned earlier, little data was available about the setup and inventory cots. These costs are always difficult to determine, but little research has been done on these costs. It was time consuming to collect all information and do all calculations to get an accurate estimation of the setup and inventory costs.
- In our model in Section 4.2, we designed our mathematical model. In this model we assume the production quantities to be an integer value because no products are partially filled. In Section 5.5.2 we remove this integer constraint, which drastically reduces the computation time. Due to the large production quantities, it would be better to consider the production quantity X_{it} as a continuous variable already in Section 4.2 because rounding these production values will have little impact on the tactical production planning and the total costs. This would enlarge the possibility to obtain a feasible solution earlier in this research.

6.4 FURTHER RESEARCH

In our research, we considered improving the optimal stock levels by choosing drumbeat patterns for all SKUs. We developed a MILP and developed multiple models to improve the tactical production planning. Nevertheless, we did not research all areas that are related to this problem in our research. For this reason, we consider the recommendations for future research in this section.

- We already recommend converting our mathematical model into another program or to use a heuristic to solve the problem towards optimality. To find out which program or heuristic is most suitable for this problem, more research and experiments need to be done in this area.
- As written in the recommendations to FrieslandCampina, it is wise to research other methods to obtain a solution to the problem of this research. We made a first step towards column generation when solving the model of all packaging lines included. This algorithm focuses on only the variables which have the potential to improve the objective function. With this algorithm is it likely to find an even better or optimal solution. Based on the drumbeat patterns chosen in the optimal solution per packaging line, subsets could be made to only include variables which have the potential to improve the objective function. On the other hand, a heuristic is a useful tool to obtain a solution is less computation time. Simulated annealing will be likely to be a good fit as we discussed in our literature review. However, new research is should rule out which approach is best for the problem in our research.
- The drumbeat patterns are chosen at the product family level. Therefore, it is important how these product families are composed. In our research, we composed these product families based on the CIP's needed and with the information given by the supply network planners. Extensive research can be done on the impact of these composed product families. If we make a small adjustment in the product families, what is the impact on the tactical production planning? In addition, a literature review can be carried out on methods for compiling these product families.

- The model in this research is based on the forecast of 24 weeks. It would be valuable to run the models with another forecast period. A comparison could give insight into the difference in drumbeat patterns between different seasonality's. Due to time constraints, these extra runs could not be made but will be valuable for FrieslandCampina.
- As mentioned in Section 6.2.1 the setup and inventory costs were difficult to determine. More research can be done into the actual costs of the various processes in the plant. This will be beneficial for many more studies to come. In addition, major outliers can be identified and reduced.
- Our model does not take the shelf life of the products into account. This is not necessary in most cases, as the drumbeat patterns ensure that the product at least once every four weeks. In an extension of our mathematical model, more drumbeat patterns can be added. If it is possible to choose a drumbeat pattern with only one production moment every eight weeks, it is important to include the shelf life.
- In our research, we assume that there is no limit to the stock level. It is difficult to add this because the products are stored in many different warehouses. Nevertheless, it is interesting to add this to the model or at least analyze whether any limits are exceeded here.

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APPENDIX

A. Mathematical models

In this appendix, the mathematical models of four different situations are written down. In the table below we show the differences between the four models.

Table 30: Different MILPs

Model	Multiple packaging lines	Format changeovers
Model 1	YES	YES
Model 2	YES	NO
Model 3	NO	YES
Model 4	NO	NO

Model 1: Multiple packaging lines with format changeovers

Indices

I	$Set\ of\ product\ i\ (\mathrm{i} = 1, \ldots, \mathrm{I})$
I_f	$Set\ of\ products\ i\ in\ product\ family\ f\ (\mathrm{f} = 1, \ldots, \mathrm{F})$
I_r	$Set\ of\ product\ i\ made\ by\ recipe\ r\ (\mathrm{r} = 1, \ldots, \mathrm{R})$
I_u	$Set\ of\ product\ i\ with\ format\ u\ (\mathrm{u} = 1, \ldots, \mathrm{U})$
T	$Set\ of\ time\ periods\ t\ (\mathrm{t} = 1, \ldots, \mathrm{T})$
N	$Set\ of\ drumbeats\ patterns\ n\ (\mathrm{n} = 1, \ldots, \mathrm{N})$
K	$Set\ of\ packaging\ lines\ k\ (\mathrm{k} = 1, \ldots, \mathrm{K})$

Parameters

d_{it}	$Forecast\ for\ product\ i\ in\ time\ period\ t$
c_{tk}	$Available\ capacity\ in\ time\ period\ t\ at\ line\ k$
a_{it}	$Safety\ stock\ required\ for\ product\ i\ in\ time\ period\ t$
p_{ik}	$Unit\ resource\ consumption\ for\ product\ i\ on\ packaging\ line\ k$
v_i	$Format\ in\ liters\ of\ product\ i$
MOQ_r	$Minimal\ production\ quantity\ for\ recipe\ r$
MAX_r	$Maximum\ production\ quantity\ for\ recipe\ r$
h_{it}	$Unit\ inventory\ costs\ for\ product\ i\ at\ the\ end\ of\ period\ t$
s_{ftk}	$Setup\ costs\ incurred\ if\ product\ family\ f\ is\ produced\ in\ time\ period\ t\ at\ line\ k$
t_{ftk}	$Setup\ time\ inccured\ if\ product\ family\ f\ is\ produced\ in\ time\ period\ t\ at\ line\ k$
s_{rtk}	$Setup\ costs\ incurred\ if\ recipe\ r\ is\ produced\ in\ time\ period\ t\ at\ line\ k$
t_{rtk}	$Setup\ time\ inccured\ if\ recipe\ r\ is\ produced\ in\ time\ period\ t\ at\ line\ k$
s_{utk}	$Setup\ costs\ incurred\ if\ format\ changeover\ u\ is\ required\ in\ time\ period\ t\ at\ line\ k$
t_{utk}	$Setup\ time\ inccured\ if\ format\ changeover\ u\ is\ required\ in\ time\ period\ t\ at\ line\ k$
M	$A\ Large\ number$

$$b_{nt} = \begin{cases} 1, if\ drumbeat\ n\ allows\ production\ in\ time\ period\ t \\ 0, otherwise \end{cases}$$

$I_{io} = \sum_{k=1}^{4} d_{ik} + a_{i4}$ $\quad Starting\ inventory\ for\ product\ i\ in\ the\ first\ time\ period$

Decision variables & auxiliary decision variables

$$Q_{fn} \quad = \begin{cases} 1, if\ for\ product\ family\ f\ drumbeat\ pattern\ n\ is\ chosen \\ 0, otherwise \end{cases}$$

X_{it} $\quad$ $Production\ quantity\ of\ product\ i\ in\ time\ period\ t$

I_{it} $\quad$ $Inventory\ for\ product\ i\ at\ the\ end\ of\ time\ period\ t$

$$Z_{ftk} \quad = \begin{cases} 1, if\ there\ is\ production\ for\ product\ family\ f\ in\ time\ period\ t\ at\ line\ k \\ 0, otherwise \end{cases}$$

$$W_{rtk} \quad = \begin{cases} 1, if\ there\ is\ production\ for\ recipe\ r\ in\ time\ period\ t\ at\ line\ k \\ 0, otherwise \end{cases}$$

$$G_{rt} \quad = \begin{cases} 1, if\ there\ is\ production\ for\ recipe\ r\ in\ time\ period\ t \\ 0, otherwise \end{cases}$$

$$J_{utk} \quad = \begin{cases} 1, if\ a\ format\ changeover\ is\ required\ to\ format\ u\ in\ time\ period\ t\ at\ line\ k \\ 0, otherwise \end{cases}$$

Objective function

Minimize
$$Z = \sum_{f=1}^{F}\sum_{t=1}^{T}\sum_{k=1}^{K}(s_{ftk} * Z_{ftk}) + \sum_{r=1}^{R}\sum_{t=1}^{T}\sum_{k=1}^{K}(s_{rtk} * W_{rtk}) + \sum_{u=1}^{U}\sum_{t=1}^{T}\sum_{k=1}^{K}(s_{utk} * J_{utk}) + \sum_{i=1}^{I}\sum_{t=1}^{T}(h_{it} * I_{it}) \tag{1}$$

Constraints

$$\sum_{i=1}^{I} p_{ik} * X_{it} + \sum_{f=1}^{F} Z_{ftk} * t_{ftk} + \sum_{r=1}^{R} W_{rtk} * t_{rtk} + \sum_{u=1}^{U} J_{utk} * t_{utk} \leq c_{tk}, \quad \forall t \in T, \forall k \in K \tag{2}$$

$$X_{it} + I_{i,t-1} - I_{it} = d_{it}, \qquad \forall i \in I, \forall t \in T \tag{3}$$

$$I_{it} \geq a_{it}, \qquad \forall i \in I, \forall t \in T \tag{4}$$

$$\sum_{n=1}^{N} Q_{fn} = 1, \qquad \forall f \in F \tag{5}$$

$$Z_{ftk} = \sum_{n=1}^{N}(Q_{fn} * b_{nt}), \qquad \forall f \in F, \forall t \in T, \forall k \in K \tag{6}$$

$$\sum_{i=1}^{I_r} X_{it} \leq M * W_{rtk}, \qquad \forall r \in R, \forall t \in T, \forall k \in K \tag{7}$$

$$\sum_{k=1}^{K} W_{rtk} \leq M * G_{rt}, \qquad \forall r \in R, \forall t \in T \tag{8}$$

$$\sum_{i=1}^{i \in I_u} X_{it} \leq M * J_{utk} \qquad \forall u \in U, \forall t \in T, \forall k \in K \tag{9}$$

$$X_{it} \leq M * Z_{ftk}, \qquad \forall i \in I_f, \forall t \in T \tag{10}$$

$$\sum_{i=1}^{i \in I_r}(X_{it} * v_i) \geq MOQ_r * G_{rt}, \qquad \forall r \in R, \forall t \in T \tag{11}$$

$$\sum_{i=1}^{i \in I_r}(X_{it} * v_i) \leq MAX_r * G_{rt}, \qquad \forall r \in R, \forall t \in T \tag{12}$$

$$X_{it}, I_{it} \geq 0 \qquad \forall i \in I, \forall t \in T \tag{13}$$

$$Q_{fn} \in \{0,1\} \qquad \forall f \in F, \forall n \in N \tag{14}$$

$$Z_{ftk} \in \{0,1\} \qquad \forall f \in F, \forall t \in T, \forall k \in K \tag{15}$$

$W_{rtk} \quad \in \{0,1\} \qquad \forall r \in R, \forall t \in T, \forall k \in K \qquad (16)$

$G_{rt} \quad \in \{0,1\} \qquad \forall r \in R, \forall t \in T \qquad (17)$

$J_{utk} \quad \in \{0,1\} \qquad \forall u \in U, \forall t \in T, \forall k \in K \qquad (18)$

Model 2: Multiple packaging lines without format changeovers

Indices

I	$Set\ of\ product\ i$ (i = 1, ..., I)
I_f	$Set\ of\ products\ i\ in\ product\ family\ f$ (f = 1, ..., F)
I_r	$Set\ of\ product\ i\ made\ by\ recipe\ r$ (r = 1, ..., R)
T	$Set\ of\ time\ periods\ t$ (t = 1, ..., T)
N	$Set\ of\ drumbeat\ patterns\ n$ (n = 1, ..., N)
K	$Set\ of\ packaging\ lines\ k$ (k = 1, ..., K)

Parameters

d_{it}	$Forecast\ for\ product\ i\ in\ time\ period\ t$
c_{tk}	$Available\ capacity\ in\ time\ period\ t\ at\ line\ k$
a_{it}	$Safety\ stock\ required\ for\ product\ i\ in\ time\ period\ t$
p_{ik}	$Unit\ resource\ consumption\ for\ product\ i\ on\ packaging\ line\ k$
v_i	$Format\ in\ liters\ of\ product\ i$
MOQ_r	$Minimal\ production\ quantity\ for\ recipe\ r$
MAX_r	$Maximum\ production\ quantity\ for\ recipe\ r$
h_{it}	$Unit\ inventory\ costs\ for\ product\ i\ at\ the\ end\ of\ period\ t$
s_{ftk}	$Setup\ costs\ incurred\ if\ product\ family\ f\ is\ produced\ in\ time\ period\ t\ at\ line\ k$
t_{ftk}	$Setup\ time\ inccured\ if\ product\ family\ f\ is\ produced\ in\ time\ period\ t\ at\ line\ k$
s_{rtk}	$Setup\ costs\ incurred\ if\ recipe\ r\ is\ produced\ in\ time\ period\ t\ at\ line\ k$
t_{rtk}	$Setup\ time\ inccured\ if\ recipe\ r\ is\ produced\ in\ time\ period\ t\ at\ line\ k$
M	$A\ Large\ number$

$$b_{nt} \quad = \begin{cases} 1, if\ drumbeat\ n\ allows\ production\ in\ time\ period\ t \\ 0, otherwise \end{cases}$$

$I_{io} = \sum_{k=1}^{4} d_{ik} + a_{i4} \qquad Starting\ inventory\ for\ product\ i\ in\ the\ first\ time\ period$

Decision variables & auxiliary decision variables

$$Q_{fn} \quad = \begin{cases} 1, if\ for\ product\ family\ f\ drumbeat\ pattern\ n\ is\ chosen \\ 0, otherwise \end{cases}$$

X_{it}	$Production\ quantity\ of\ product\ i\ in\ time\ period\ t$
I_{it}	$Inventory\ for\ product\ i\ at\ the\ end\ of\ time\ period\ t$

$$Z_{ftk} \quad = \begin{cases} 1, if\ there\ is\ production\ for\ product\ family\ f\ in\ time\ period\ t\ at\ line\ k \\ 0, otherwise \end{cases}$$

$$W_{rtk} \quad = \begin{cases} 1, if\ there\ is\ production\ for\ recipe\ r\ in\ time\ period\ t\ at\ line\ k \\ 0, otherwise \end{cases}$$

$$G_{rt} \quad = \begin{cases} 1, if\ there\ is\ production\ for\ recipe\ r\ in\ time\ period\ t \\ 0, otherwise \end{cases}$$

Objective function

Minimize $Z = \sum_{f=1}^{F}\sum_{t=1}^{T}\sum_{k=1}^{K}(s_{ftk} * Z_{ftk}) + \sum_{r=1}^{R}\sum_{t=1}^{T}\sum_{k=1}^{K}(s_{rtk} * W_{rtk}) + \sum_{i=1}^{I}\sum_{t=1}^{T}(h_{it} * I_{it})$ (1)

Constraints

$\sum_{i=1}^{I} p_{ik} * X_{it} + \sum_{f=1}^{F} Z_{ftk} * t_{ftk} + \sum_{r=1}^{R} W_{rtk} * t_{rtk} \leq c_{tk},$ $\forall t \in T, \forall k \in K$ (2)

$X_{it} + I_{i,t-1} - I_{it} = d_{it},$ $\forall i \in I, \forall t \in T$ (3)

$I_{it} \geq a_{it},$ $\forall i \in I, \forall t \in T$ (4)

$\sum_{n=1}^{N} Q_{fn} = 1,$ $\forall f \in F$ (5)

$Z_{ftk} = \sum_{n=1}^{N}(Q_{fn} * b_{nt}),$ $\forall f \in F, \forall t \in T, \forall k \in K$ (6)

$\sum_{i=1}^{I_r} X_{it} \leq M * W_{rtk},$ $\forall r \in R, \forall t \in T, \forall k \in K$ (7)

$\sum_{k=1}^{K} W_{rtk} \leq M * G_{rt},$ $\forall r \in R, \forall t \in T$ (8)

$X_{it} \leq M * Z_{ftk},$ $\forall i \in I_f, \forall t \in T$ (9)

$\sum_{i=1}^{i \in I_r}(X_{it} * v_i) \geq MOQ_r * G_{rt},$ $\forall r \in R, \forall t \in T$ (10)

$\sum_{i=1}^{i \in I_r}(X_{it} * v_i) \leq MAX_r * G_{rt},$ $\forall r \in R, \forall t \in T$ (11)

$X_{it}, I_{it} \geq 0$ $\forall i \in I, \forall t \in T$ (12)

$Q_{fn} \in \{0,1\}$ $\forall f \in F, \forall n \in N$ (13)

$Z_{ftk} \in \{0,1\}$ $\forall f \in F, \forall t \in T, \forall k \in K$ (14)

$W_{rtk} \in \{0,1\}$ $\forall r \in R, \forall t \in T, \forall k \in K$ (15)

$G_{rt} \in \{0,1\}$ $\forall r \in R, \forall t \in T$ (16)

Model 3: Single packaging line with format changeovers

Indices

I	$Set\ of\ product\ i$ (i = 1,…, I)
I_f	$Set\ of\ products\ i\ in\ product\ family\ f$ (f = 1,…, F)
I_r	$Set\ of\ product\ i\ made\ by\ recipe\ r$ (r = 1,…, R)
I_u	$Set\ of\ product\ i\ with\ format\ u$ (u = 1,…, U)
T	$Set\ of\ time\ periods\ t$ (t = 1,…, T)
N	$Set\ of\ drumbeat\ patterns\ n$ (n = 1,…, N)

Parameters

d_{it}	$Forecast\ for\ product\ i\ in\ time\ period\ t$
c_t	$Available\ capacity\ in\ time\ period\ t$
a_{it}	$Safety\ stock\ required\ for\ product\ i\ in\ time\ period\ t$
p_i	$Unit\ resource\ consumption\ for\ product\ i$

v_i	$Format\ in\ liters\ of\ product\ i$
MOQ_r	$Minimal\ production\ quantity\ for\ recipe\ r$
MAX_r	$Maximum\ production\ quantity\ for\ recipe\ r$
h_{it}	$Unit\ inventory\ costs\ for\ product\ i\ at\ the\ end\ of\ period\ t$
s_{ft}	$Setup\ costs\ incurred\ if\ product\ family\ f\ is\ produced\ in\ time\ period\ t$
t_{ft}	$Setup\ time\ inccured\ if\ product\ family\ f\ is\ produced\ in\ time\ period\ t$
s_{rt}	$Setup\ costs\ incurred\ if\ recipe\ r\ is\ produced\ in\ time\ period\ t$
t_{rt}	$Setup\ time\ inccured\ if\ recipe\ r\ is\ produced\ in\ time\ period\ t$
s_{ut}	$Setup\ costs\ incurred\ if\ format\ changeover\ u\ is\ required\ in\ time\ period\ t$
t_{ut}	$Setup\ time\ inccured\ if\ format\ changeover\ u\ is\ required\ in\ time\ period\ t$
M	$A\ Large\ number$

$$b_{nt} = \begin{cases} 1, if\ drumbeat\ n\ allows\ production\ in\ time\ period\ t \\ 0, otherwise \end{cases}$$

$I_{io} = \sum_{k=1}^{4} d_{ik} + a_{i4}$ $\quad Starting\ inventory\ for\ product\ i\ in\ the\ first\ time\ period$

Decision variables & auxiliary decision variables

$$Q_{fn} = \begin{cases} 1, if\ for\ product\ family\ f\ drumbeat\ n\ is\ chosen \\ 0, otherwise \end{cases}$$

X_{it}	$Production\ quantity\ of\ product\ i\ in\ time\ period\ t$
I_{it}	$Inventory\ for\ product\ i\ at\ the\ end\ of\ time\ period\ t$

$$Z_{ft} = \begin{cases} 1, if\ there\ is\ production\ for\ product\ family\ f\ in\ time\ period\ t \\ 0, otherwise \end{cases}$$

$$G_{rt} = \begin{cases} 1, if\ there\ is\ production\ for\ recipe\ r\ in\ time\ period\ t \\ 0, otherwise \end{cases}$$

$$J_{ut} = \begin{cases} 1, if\ a\ format\ changeover\ is\ required\ to\ format\ u\ in\ time\ period\ t \\ 0, otherwise \end{cases}$$

Objective function

Minimize $$Z = \sum_{f=1}^{F} \sum_{t=1}^{T} (S_{ft} * Z_{ft}) + \sum_{r=1}^{R} \sum_{t=1}^{T} (S_{rt} * W_{rt}) + \sum_{u=1}^{U} \sum_{t=1}^{T} (S_{ut} * J_{ut}) + \sum_{i=1}^{I} \sum_{t=1}^{T} (h_{it} * I_{it}) \quad (1)$$

Constraints

$$\sum_{i=1}^{I} p_i * X_{it} + \sum_{f=1}^{F} Z_{ft} * t_{ft} + \sum_{r=1}^{R} W_{rt} * t_{rt} + \sum_{u=1}^{U} J_{ut} * t_{ut} \leq c_t, \quad \forall t \in T \quad (2)$$

$$X_{it} + I_{i,t-1} - I_{it} = d_{it}, \quad \forall i \in I, \forall t \in T \quad (3)$$

$$I_{it} \geq a_{it}, \quad \forall i \in I, \forall t \in T \quad (4)$$

$$\sum_{n=1}^{N} Q_{fn} = 1, \quad \forall f \in F \quad (5)$$

$$Z_{ft} = \sum_{n=1}^{N} (Q_{fn} * b_{nt}), \quad \forall f \in F, \forall t \in T \quad (6)$$

$$\sum_{i=1}^{I_r} X_{it} \leq M * G_{rt}, \quad \forall r \in R, \forall t \in T \quad (7)$$

$\sum_{i=1}^{i \in I_u} X_{it} \leq M * J_{ut}$ $\forall u \in U, \forall t \in T$ (8)

$X_{it} \leq M * Z_{ft},$ $\forall i \in I_f, \forall t \in T$ (9)

$\sum_{i=1}^{i \in I_r} (X_{it} * v_i) \geq MOQ_r * G_{rt},$ $\forall r \in R, \forall t \in T$ (10)

$\sum_{i=1}^{i \in I_r} (X_{it} * v_i) \leq MAX_r * G_{rt},$ $\forall r \in R, \forall t \in T$ (11)

$X_{it}, I_{it} \geq 0$ $\forall i \in I, \forall t \in T$ (12)

$Q_{fn} \in \{0,1\}$ $\forall f \in F, \forall n \in N$ (13)

$Z_{ft} \in \{0,1\}$ $\forall f \in F, \forall t \in T$ (14)

$G_{rt} \in \{0,1\}$ $\forall r \in R, \forall t \in T$ (15)

$J_{ut} \in \{0,1\}$ $\forall u \in U, \forall t \in T$ (16)

Model 4: Single packaging line without format changeovers

Indices

I	$Set\ of\ product\ i$ $(\mathrm{i} = 1, \dots, \mathrm{I})$
I_f	$Set\ of\ products\ i\ in\ product\ family\ f$ $(\mathrm{f} = 1, \dots, \mathrm{F})$
I_r	$Set\ of\ product\ i\ made\ by\ recipe\ r$ $(\mathrm{r} = 1, \dots, \mathrm{R})$
T	$Set\ of\ time\ periods\ t$ $(\mathrm{t} = 1, \dots, \mathrm{T})$
N	$Set\ of\ drumbeat\ patterns\ n$ $(\mathrm{n} = 1, \dots, \mathrm{N})$

Parameters

d_{it}	$Forecast\ for\ product\ i\ in\ time\ period\ t$
c_t	$Available\ capacity\ in\ time\ period\ t$
a_{it}	$Safety\ stock\ required\ for\ product\ i\ in\ time\ period\ t$
p_i	$Unit\ resource\ consumption\ for\ product\ i$
v_i	$Format\ in\ liters\ of\ product\ i$
MOQ_r	$Minimal\ production\ quantity\ for\ recipe\ r$
MAX_r	$Maximum\ production\ quantity\ for\ recipe\ r$
h_{it}	$Unit\ inventory\ costs\ for\ product\ i\ at\ the\ end\ of\ period\ t$
s_{ft}	$Setup\ costs\ incurred\ if\ product\ family\ f\ is\ produced\ in\ time\ period\ t$
t_{ft}	$Setup\ time\ inccured\ if\ product\ family\ f\ is\ produced\ in\ time\ period\ t$
s_{rt}	$Setup\ costs\ incurred\ if\ recipe\ r\ is\ produced\ in\ time\ period\ t$
t_{rt}	$Setup\ time\ inccured\ if\ recipe\ r\ is\ produced\ in\ time\ period\ t$
M	$A\ Large\ number$

$$b_{nt} = \begin{cases} 1, if\ drumbeat\ n\ allows\ production\ in\ time\ period\ t \\ 0, otherwise \end{cases}$$

$I_{io} = \sum_{k=1}^{4} d_{ik} + a_{i4}$ $Starting\ inventory\ for\ product\ i\ in\ the\ first\ time\ period$

Decision variables & auxiliary decision variables

Q_{fn} $= \begin{cases} 1, if\ for\ product\ family\ f\ drumbeat\ n\ is\ chosen \\ 0, otherwise \end{cases}$

X_{it} $\quad Production\ quantity\ of\ product\ i\ in\ time\ period\ t$

I_{it} $\quad Inventory\ for\ product\ i\ at\ the\ end\ of\ time\ period\ t$

Z_{ft} $= \begin{cases} 1, if\ there\ is\ production\ for\ product\ family\ f\ in\ time\ period\ t \\ 0, otherwise \end{cases}$

G_{rt} $= \begin{cases} 1, if\ there\ is\ production\ for\ recipe\ r\ in\ time\ period\ t \\ 0, otherwise \end{cases}$

Objective function

Minimize

$$Z = \sum_{f=1}^{F} \sum_{t=1}^{T} (S_{ft} * Z_{ft}) + \sum_{r=1}^{R} \sum_{t=1}^{T} (S_{rt} * W_{rt}) + \sum_{i=1}^{I} \sum_{t=1}^{T} (h_{it} * I_{it}) \qquad (1)$$

Constraints

$\sum_{i=1}^{I} p_i * X_{it} + \sum_{f=1}^{F} Z_{ft} * t_{ft} + \sum_{r=1}^{R} W_{rt} * t_{rt} \leq c_t,$ $\quad \forall t \in T$ $\quad$ (2)

$X_{it} + I_{i,t-1} - I_{it} = d_{it},$ $\quad \forall i \in I, \forall t \in T$ $\quad$ (3)

$I_{it} \geq a_{it},$ $\quad \forall i \in I, \forall t \in T$ $\quad$ (4)

$\sum_{n=1}^{N} Q_{fn} = 1,$ $\quad \forall f \in F$ $\quad$ (5)

$Z_{ft} = \sum_{n=1}^{N} (Q_{fn} * b_{nt}),$ $\quad \forall f \in F, \forall t \in T$ $\quad$ (6)

$\sum_{i=1}^{I_r} X_{it} \leq M * G_{rt},$ $\quad \forall r \in R, \forall t \in T$ $\quad$ (7)

$X_{it} \leq M * Z_{ft},$ $\quad \forall i \in I_f, \forall t \in T$ $\quad$ (8)

$\sum_{i=1}^{i \in I_r} (X_{it} * v_i) \geq MOQ_r * G_{rt},$ $\quad \forall r \in R, \forall t \in T$ $\quad$ (9)

$\sum_{i=1}^{i \in I_r} (X_{it} * v_i) \leq MAX_r * G_{rt},$ $\quad \forall r \in R, \forall t \in T$ $\quad$ (10)

$X_{it}, I_{it} \geq 0$ $\quad \forall i \in I, \forall t \in T$ $\quad$ (11)

$Q_{fn} \in \{0,1\}$ $\quad \forall f \in F, \forall n \in N$ $\quad$ (12)

$Z_{ft} \in \{0,1\}$ $\quad \forall f \in F, \forall t \in T$ $\quad$ (13)

$G_{rt} \in \{0,1\}$ $\quad \forall r \in R, \forall t \in T$ $\quad$ (14)

B. Results of the models with less drumbeat patterns

In this appendix, we show the results of the experiments in which we reduced the number of drumbeat pattern options. Table 31 provides an overview of the capacity utilization in percentages. In Table 32 we show the utilization of the maximum production quantities in percentages of a few weeks. The analysis of this information is written in Section 5.5.1.

Table 31: Changes in the capacity utilization in the models (LD)

Line	**CURRENT CAPACITY USE**				**CAPACITY RESULTS MODEL (LD)**				**Average savings**
	Week 1	Week 2	Week 3	Week 4	Week 1	Week 2	Week 3	Week 4	
V									4%
U									2%
T									-8%
R									-9%
A									-1%
C									-6%
E+F									2%
G+H									0%
I+J									20%
K									13%
L									-8%
X									-1%
Y									3%
Z									-3%
TOTAL									**2%**

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Table 32: Percentages of maximum production quantities used in models (LD)

Recipe category	**Maximum**	**W5**	**W6**	**W7**	**W8**	**W9**	**W10**	**W11**	**W12**
Milk		0	0	0	0	0	0	0	0
Evap		0	0	0	0	0	0	0	0
Buttermilk		0	0	0	0	0	0	0	0
Flavoured Milk		0	0	0	0	0	0	0	0
Cream		1	0	0	0	1	0	1	0
CCM		0	0	0	0	0	0	0	0

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C. Results of the models with no integer constraint

In this appendix, we show the results of the experiments in which we removed the integer constraint of the production quantity variables. Table 33 provides an overview of the capacity utilization in percentages. In Table 34 we show the utilization of the maximum production quantities in percentages of a few weeks. The analysis of this information is written in Section 5.5.2.

Table 33: Changes in the capacity utilization in the models (NI)

Line	**CURRENT CAPACITY USE**				**CAPACITY RESULTS MODEL (NI)**				**Average savings**
	Week 1	Week 2	Week 3	Week 4	Week 1	Week 2	Week 3	Week 4	
V									4%
U									4%
T									-3%
R									-8%
A									-3%
C									-3%
E+F									2%
G+H									-3%
I+J									17%
K									12%
L									-1%
X									-2%
Y									1%
Z									-6%
TOTAL									**2%**

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Table 34: Percentages of maximum production quantities used in models (NI)

Recipe category	**Maximum**	**W5**	**W6**	**W7**	**W8**	**W9**	**W10**	**W11**	**W12**
Milk		0	0	0	0	0	0	0	0
Evap		0	0	0	0	0	0	0	0
Buttermilk		0	0	0	0	0	0	0	0
Flavoured Milk		0	0	0	0	0	0	0	0
Cream		1	1	0	0	1	1	0	0
CCM		0	0	0	0	0	0	0	0

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D. RESULTS OF THE MODELS WITH LESS DRUMBEAT PATTERNS AND NO INTEGER CONSTRAINT

In this appendix, we show the results of the experiments in which we reduced the drumbeat pattern options and removed the integer constraint of the production quantities. Table 35 provides an overview of the capacity utilization in percentages. In Table 36 we show the utilization of the maximum production quantities in percentages of a few weeks. The analysis of this information is written in Section 5.5.3.

Table 35: Changes in the capacity utilization in the models (LD+NI)

Line	CURRENT CAPACITY USE				CAPACITY RESULTS MODEL (LD+NI)				Average savings
	Week 1	Week 2	Week 3	Week 4	Week 1	Week 2	Week 3	Week 4	
V									5%
U									6%
T									-7%
R									-7%
A									-3%
C									-1%
E+F									4%
G+H									0%
I+J									17%
K									15%
L									-1%
X									-3%
Y									5%
Z									-3%
TOTAL									**4%**

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Table 36: Percentages of maximum production quantities used in models (LD+NI)

Recipe category	Maximum	W5	W6	W7	W8	W9	W10	W11	W12
Milk		0	0	0	0	0	0	0	0
Evap		0	0	0	0	0	0	0	0
Buttermilk		0	0	0	0	0	0	0	0
Flavoured Milk		0	0	0	0	0	0	0	0
Cream		1	0	1	0	1	0	1	0
CCM		0	0	0	0	0	0	0	0

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E. Results of the model with all packaging lines included

In this appendix, we show the results of the model in which all packaging lines are included. In addition, we removed the integer constraint of the production quantities and we used two subsets of drumbeat pattern options. Table 37 provides an overview of the capacity utilization in percentages for each packaging line. In Table 38 we show the utilization of the maximum production quantities in percentages of a few weeks. The analysis of this information is written in Section 5.5.4.

Table 37: Changes in the capacity utilization in the model with all packaging lines included

Line	CURRENT CAPACITY USE				CAPACITY RESULTS MODEL				Average savings
	Week 1	Week 2	Week 3	Week 4	Week 1	Week 2	Week 3	Week 4	
V									3%
U									5%
T									2%
R									-8%
A									0%
C									-2%
E+F									5%
G+H									3%
I+J									17%
K									12%
L									0%
X									3%
Y									5%
Z									-1%
TOTAL									**5%**

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Table 38: Percentages of maximum production quantities used in the model with all packaging lines included

Recipe category	Maximum	W5	W6	W7	W8	W9	W10	W11	W12
Milk		0	0	0	0	0	0	0	0
Evap		0	0	0	0	0	0	0	0
Buttermilk		0	0	0	0	0	0	0	0
Flavoured Milk		0	0	0	0	0	0	0	0
Cream		1	1	1	1	1	1	0	0
CCM		0	0	0	0	0	0	0	0

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